

AN ANNOTATED HISTORY OF
CONTAINER CANDIDATE MATERIAL SELECTION

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July 1988

Lawrence
Livermore
National
Laboratory

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

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Code**

**Page
Range**

A01

Microfiche

Papercopy Prices

A02

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Prepared by Yucca Mountain Project (YMP) participants as part of the Civilian Radioactive Waste Management Program. The YMP project is managed by the Waste Management Project Office of the U.S. Department of Energy, Nevada Operations Office. YMP Project work is sponsored by the DOE Office of Civilian Radioactive Waste Management.

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Abstract

This paper documents events in the Nevada Nuclear Waste Storage Investigations (NNWSI) Project that have influenced the selection of metals and alloys proposed for fabrication of waste package containers for permanent disposal of high-level nuclear waste in a repository at Yucca Mountain, Nevada. The time period from 1981 to 1988 is covered in this annotated history. The history traces the candidate materials that have been considered at different stages of site characterization planning activities. At present, six candidate materials are considered and described in the 1988 Consultation Draft of the NNWSI Site Characterization Plan (SCP). The six materials are grouped into two alloy families, copper-base materials and iron to nickel-base materials with an austenitic structure. The three austenitic candidates resulted from a 1983 survey of a longer list of candidate materials; the other three candidates resulted from a special request from DOE in 1984 to evaluate copper and copper-base alloys.

1.0 INTRODUCTION

The purpose of this paper is to document the history of the part of the Metal Barrier Selection and Testing Task that concerns selection of candidate materials for the waste package container. This paper covers events in the time period 1981-88. Monthly status reports, letters, memos, formal reports or other documentation exist; as appropriate, these are discussed and cited. Many of the relevant pieces of internal correspondence that did not receive general Project-wide distribution are attached to this paper.

The waste package container is part of a system of multiple engineered and natural barriers barriers that are being designed and used for geologic disposal of high-level nuclear waste. The Department of Energy's Office of Civilian Radioactive Waste Management (OCRWM) is engaged in the development of a geological repository for the disposal of U.S. high-level nuclear waste, as directed by the Nuclear Waste Policy Act of 1982. The Nevada Nuclear Waste Storage Investigations (NNWSI) Project is evaluating a site located in tuff rock at Yucca Mountain in southern Nevada. Lawrence-Livermore National Laboratory (LLNL) has the responsibility for design, testing, and performance analysis of waste packages for this site.

Various Federal regulations, established by the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA), set limits on the release of radionuclides from the repository. NRC regulation 10CFR60 specifies that containment of radionuclides will be substantially complete for a period of time yet to be determined, with a minimum period of 300 years and a maximum period of 1000 years after repository closure. Following this containment period, the regulation limits the release rate of any radionuclide from the engineered barrier system to one part in 100,000 per year of the inventory of that radionuclide present at 1000 years. EPA regulation 40CFR191 sets limits for the cumulative releases of specific radionuclides to the accessible environment over a period of 10,000 years after disposal. NRC regulation 10CFR60 also specifies that the waste must be retrievable for a period of 50 years after emplacement. The waste package container therefore plays an important role in the handling and retrieval capability of the waste, as well as waste containment and later, release rate limitation.

1.1 Present Candidate Container Materials

The Metal Barrier Selection and Testing Task is currently evaluating six container candidate materials. These container materials are generally grouped into two "alloy families". These "families" are (A) the iron-base to nickel-base austenitic alloys and (B) the copper-base materials. The NNWSI Project has been evaluating and testing materials in the austenitic group since 1982, while the evaluation of the copper-base materials dates from 1984. There are presently three "austenitic candidates":

- (1) AISI 304L stainless steel (UNS S30403);
- (2) AISI 316L stainless steel (UNS S31603);
- (3) nickel-base alloy 825 (UNS N08825).

The current list of three copper-base candidate materials consists of:

- (1) CDA 102, oxygen-free copper (UNS C10200);
- (2) CDA 613, 7% aluminum bronze (UNS C61300);
- (3) CDA 715, 70/30 copper-nickel (UNS C71500).

Recently, the NNWSI Project has also considered deoxidized coppers, specifically phosphorus deoxidized copper (CDA 122, UNS C12200), as a "variant" of the high purity copper, since there are some important welding concerns with the oxygen-free grade. For reference purposes, a listing of the compositions of the candidate materials is given in Attachment A.

1.2 Status and Documentation

Documents recently completed (1987-88) by the Metal Barrier Selection and Testing Task are the Scientific Investigation Plan (SIP) [ref 1] and parts of the Consultation Draft of the Site

Characterization Plan (SCP) [ref 2], specifically Sections 7.4.2 and 8.3.5.9. These documents describe the recent status of the work and outline plans for future work up through the License Application Design (LAD) phase. The NNWSI Project has currently progressed to a stage of development between the Conceptual Design and the Advanced Conceptual Design (ACD) phases. A brief summary of the status and plans is given in Section 4.0 of this paper.

1.3 Waste Package Container Terminology

There has occasionally been some ambiguity on the terminology for the waste package metal barrier. Metal barriers have been variously called containers, canisters, and overpacks. Different projects (USA and foreign) have used the words in different senses. This has been reflected in the words used in the early reports (1981-84); since about 1985, the terminology used in the NNWSI Project has conformed to NRC usage.

The word "container" applies to the metal barrier that is designed to serve as one of the engineered barriers. The word "canister" refers to the inner metal vessel in the reprocessed waste form (borosilicate glass) packages. This vessel is the recipient for the molten glass. For this reason, we like to emphasize its purpose by calling it the "pour canister". The pour canister is not regarded as an engineered barrier, although it is certainly a component of the waste package. The word "overpack" has traditionally been used for the outer metal vessel surrounding a pour canister. In the present usage, we prefer the word "container" for this outer metal vessel. This outer vessel is considered one of the engineered barriers. To emphasize its purpose, we occasionally refer to the outer vessel as the "disposal container".

2.0 CONCEPTUAL DESIGNS OF THE WASTE PACKAGE

Discussion of conceptual designs of the waste package invokes discussion of the materials for fabrication of the waste package container. Different conceptual designs have been studied over recent years, and these different designs have influenced different container material considerations.

Work at LLNL on design of the waste package for a potential repository site in Nevada began in 1981. At that time, there was a "generic

program" on waste package materials and designs that was being co-ordinated through Battelle Columbus' Office of Nuclear Waste Isolation (ONWI). ONWI, in turn, sub-contracted much of the design work to Westinghouse Advanced Energy Systems Division (AESD). While the ONWI work was supposed to be generic for a number of possible repository sites, host geological formations, and resulting geochemical environments, the ONWI work was in actuality almost entirely

devoted to studies of waste package materials and designs for salt domes and beds (multiple sites in several states were under consideration). Thus, the "starting point" for our work was a waste package design that closely resembled the one being proposed for waste disposal in salt. The Basalt Waste Isolation Project (BWIP) was from the beginning an "integrated" project with only one major contractor participant; BWIP was independently developing designs based on a repository location below the water table at sites on the Hanford Reservation in the state of Washington.

Design work within the NNWSI Project (including work on container materials and their projected performance in the tuff rock host environment) started later than comparable work for salt and basalt. Much of the early work on materials in the NNWSI Project in the 1981-83 period followed the examples of the basalt and salt projects.

2.1 Repository Horizons

At about this same time, the location for a repository site in Nevada was being narrowed to Yucca Mountain, but different horizons for the repository were under consideration. The candidate horizons were located both above the water table, in what is called the unsaturated zone, and below the static water table, in what is called the saturated zone, at this site. The choice of horizon had many implications for the design of the waste package and ultimately on the materials to be considered for the waste package container.

Geologic repository investigations in the USA had previously been confined to sites and horizons where the repository might either eventually be inundated by water or would be located in a material, such as salt, subject to creep. Not only did this cause resistance to aqueous corrosion to be among the most important material properties for the container, but the waste package container would be required to withstand pressure from the exterior (due to the hydrostatic pressure in the case of the basalt formation or due to the lithostatic pressure in the case of the salt formation). Thus, the common feature in all designs was use of a relatively thick container that would provide sufficient thickness for mechanical strength as well as sufficient thickness to allow for the wastage of material due to aqueous corrosion. Although the salt repository environment was assumed to be initially dry, the heat produced by the waste package would favor

migration of brine inclusions in the salt toward the container surface. Because relatively thick-walled containers (on the order of 7-10 cm) were needed to withstand the environmental pressure, even thicker containers were proposed to act as radiation field attenuators. Containers with thicknesses up to 25 cm were proposed as "self-shielded waste packages". The benefit sought was that the radiation field would be reduced to a level where radiolytically induced changes in the chemical properties of the environments would be insignificant.

During FY-82, the NNWSI Project was going through a transition year. The waste package generic program at ONWI was to be phased out and each repository project was to undertake a more site-specific approach to its waste package design and selection of container materials. During FY-82 the Waste Package staff at LLNL continued to work with Westinghouse-AESD on conceptual designs for a waste package emplaced in tuff. The first "conceptual design report" for a waste package in a tuff repository was published at the end of FY-82 by Westinghouse [ref 3]. This report emphasized the self-shielded design approach and focused primarily on a repository horizon located below the water table.

The decision on which repository horizon to focus future NNWSI Project work was made in the summer of 1982. The decision was made to consider the Topopah Spring member as the location of the reference horizon for the Yucca Mountain repository; this horizon was located in the "unsaturated zone", some 300-400 meters below the surface and some 200 meters above the static water table.

2.2 Thin-Walled Containers

Consideration of a repository horizon above the water table introduced new design concept considerations. At the Yucca Mountain site, emplacement of the waste packages above the water table removed consideration of hydrostatic pressure as an environmental constraint. Furthermore, lithostatic pressure was considered negligible in the rock formation. The absence of external pressure allowed the option of using thin-walled containers (on the order of one cm) for the waste packages. However, use of thin-walled containers put greater emphasis on the resistance of the container material to all pertinent forms of environmental degradation, including oxidation in the vapor phase and aqueous corrosion in the condensed phase. This was consis-

tent with the environmental setting in that the initial emplacement conditions were expected to be dry and to remain so for a long period of time. Thus, while aqueous corrosion could occur during transient periods when water entered the repository environment, immersion of large number of containers and large areas of containers was not viewed as a likely and continuing occurrence.

Gradual consumption of the container by low temperature oxidation was therefore considered the most likely degradation mechanism affecting all of the containers for a repository horizon above the water table. In fact, it appeared that the environment itself could be controlled to prolong the container lifetime and reduce the uncertainty of failure by a non-uniform kind of aqueous corrosion. The environment could be considered as part of the engineered barrier system if the temperature could be maintained above the unconstrained boiling point of water (96 C at the proposed elevation in Yucca Mountain) for as long a period of time as possible. For spent fuel waste packages, this could be accomplished by judiciously designing the power output per container and the areal power density in laying out the configuration of the waste packages in the repository. During the 1983-88 time period, this has been a key element in the strategy for demonstrating substantially complete containment, and it has influenced the container material selection.

Designs employing thin-walled containers had other advantages. Fabrication and, especially, welding processes were viewed as less problematic on thin-walled containers than the processes that would be used to make thicker containers. With a less massive container, the handling and emplacement operations were thought to be easier to accomplish. Probably the most important factor was that the thin-walled container design resulted in significantly lower costs for both the repository and waste packages. First, less material would be used in the waste package. Second, less mining cost would be involved in excavation of the borehole. Third, less expense would be encountered in the handling and emplacement equipment needed in the repository and in the surface facilities for assembling the waste packages.

On the other hand, use of thin-walled containers placed more emphasis on the general corrosion resistance of the container material with considerable emphasis on failure by non-uniform kinds of corrosion and predicting container failure times for these modes. Also, radiolytic

changes in the environment would need to be addressed, since the thickness of the container did not substantially attenuate the dose rate (as a rough approximation, for most of the candidate metals/alloys, the radiation dose rate decreases approximately one order of magnitude for each 5 cm of container wall).

Container wall thicknesses on the order of 1 cm have been proposed for the NNWSI waste package designs since 1983. These designs were discussed in the NNWSI Conceptual Design Report [ref 6]. This thickness was coincidental with the thickness of the pour canister used for defense waste package being designed at Savannah River (at this time, NNWSI was considering using the "waste package", as it was produced, as the containment vessel). Subsequent structural and thermal analyses performed to demonstrate compliance with design requirements [ref 6] indicated that this thickness was indeed adequate for stainless steel. The highest mechanical loads would occur during waste package handling operations or under accident conditions. When copper was introduced into the NNWSI Project (1984), it appeared that somewhat thicker containers would be needed for high purity copper in order to satisfy the structural requirements. Unalloyed copper has a considerably lower yield strength than the other candidate materials, and lower creep strength under the repository thermal conditions. Finally, when the SCP was written in 1986-87 a thickness of 1-3 cm was proposed in the container designs; in addition to accommodating the lower strength materials, this would allow greater flexibility in the choices for the container fabrication processes. Moreover, in order to better distribute the stresses, it may be desirable to specify thicker end sections on the container. For example, the thicker end pieces could be made from forgings while the container body is made from rolled and welded plate.

As discussed in the 1988 Consultation Draft of the SCP, there are two general container designs, one for out-of-reactor spent fuel as a waste form, and the other for reprocessed borosilicate glass as a waste form. These waste package designs all have a common outside diameter (66 cm); the length of the waste package varies to accommodate the waste form. In the earlier years (1982-84), as documented in [ref 4, 5, and 6], there were separate designs for reprocessed defense and commercial high level waste (both proposed to be cast in a matrix form of borosilicate glass poured into a metal pour canister) corresponding to the differences in heat source density for the two waste forms. This re-

quired different dimensions for the waste packages. Since that time no more commercial spent fuel has been reprocessed in the USA. The older reprocessed commercial waste has a heat source density approximately the same as reprocessed defense waste; hence, a common design is proposed for all glass waste packages.

2.3 Plans for Site Characterization

There have been three major efforts at describing plans for site characterization for the NNWSI Project, and these efforts have involved the container material in important ways. Site characterization planning efforts have involved identification and description of container materials under consideration. The 1982 Nuclear Waste Policy Act called for preparation of important planning documents; these documents included a Mission Plan (overall schedule) and site specific reports on Environment Assessment and Site Characterization. Site characterization planning work has particularly impacted the waste package container work.

The first work on site characterization planning occurred in the summer of 1982 when the NNWSI Project was considering multiple repository horizons at Yucca Mountain. Because there were a number of possible environmental conditions (above and below the water table) and information was scant about the site, the discussion of the plan devoted to metal barrier materials was quite general. The section dealt mostly with iron and steel (cast and wrought) as container materials, but there was some consideration of more corrosion resistant materials. This draft site characterization plan was not formally published, and the subject matter was superseded when a decision was reached on the repository location later in 1982.

The second attempt at producing a comprehensive report on site characterization began in February 1983 when D. L. Vieth, then the Director of the NNWSI Project, convened many of the key participating organizations and principal investigators. The meeting was held at Holmes & Narver headquarters in Orange, California. The purpose of the meeting was to begin writing a project-wide Site Characterization Report (SCR), and this draft of that report has come to be known as the "Orange draft". This version of the SCR was never published in full, but parts of it have been used in various topical reports (including part of the metal barrier discussion). The meeting became a "write-in" with several people

spending days to weeks at Orange composing parts of the SCR. The Orange write-in concluded in late March, but portions of the SCR were later written at each contractor participant's site during the spring of 1983.

The SCR later became the SCP (Site Characterization Plan). Another unfinished draft version was started in early 1985. The present (and third) version of the SCP picked up from the 1985 work in the summer of 1986. During the remainder of 1986 and through much of 1987, this draft was composed, reviewed, and revised; it was released as a "Consultation Draft" in January 1988 (see Section 3.7). The essential format of the SCR/SCP has not changed from version to version. The plan was always to have several "data" chapters dealing with what is already known about the site and behavior of components in the site environment and then an "issue resolution and information needs" chapter outlining how different parts of the project would support one another and work toward demonstrating that the information in the license application would show compliance with the appropriate federal regulations. In the present version of the SCP, Chapter 7 discusses the work to date on the waste package, while Chapter 8 is concerned with the issue resolution and information needs.

An important advantage of the Yucca Mountain site in meeting the containment objectives was that the thermal environment could be made a part of the engineered barrier system if the temperature on the container surface could be maintained above the boiling point of water for a significant portion of the containment period. This approach has important implications for choice of the container material, because a key material property is the oxidation rate for long times at modestly elevated temperatures (up to about 250 C maximum).

An important element of the strategy for demonstrating compliance with the NRC performance objective of "substantially complete containment" as stated in the January 1988 Consultation Draft SCP is reliance on the thermal environment to maintain the conditions in a large fraction of the waste package emplacement holes such that liquid water could not be present in significant quantities for the first 300 years following closure of the repository. During the revision of the consultation draft in response to the NRC comments, it was determined that there are sufficient uncertainties in the parameters that control this thermal environment to make it infeasible to directly allocate a performance requirement to it. Therefore, in the statutory

SCP that was issued in December 1988, this topic is discussed as having the potential for improving the confidence in the ability of the waste package containers to perform their assigned function. Specific quantitative performance goals for the thermal environment are not established as an integral part of the containment strategy, but are held in reserve pending collection of the data needed to reduce the parameter uncertainties to acceptable levels. Nevertheless, the thermal energy released by radioactive decay of the waste,

primarily from fission products, will produce a local effect that will contribute to the maintenance of a "dry" environment around most of the waste packages for extended time periods both before and after the permanent closure of the repository.

An important result from the Orange draft of the SCR/SCP was the selection of "reference" features for several items in the Project. This is discussed in Section 3.2.

3.0 WASTE PACKAGE CONTAINER MATERIALS

In this section, we will pass briefly through some of the highlights of Project events and decisions that have influenced container material selection. These events will generally be discussed in chronological order, but because many activities were going on simultaneously, there is some necessary deviation from a set time pattern in discussing the subject matter and consequences of all these events.

3.1 Program Prior to the Orange Draft of the SCR

In the 1981-83 period the chief interest was in a repository location below the water table at Yucca Mountain. Also, the possibility of using thick self-shielded waste packages was being pursued. The emphasis was on comparatively inexpensive, corrosion allowance types of container materials. We began some corrosion testing of carbon steels, cast irons, and Cr-Mo low to intermediate alloy steels in the summer of 1982. Our interest in the alloy steels (e.g. 9 Cr - 1 Mo) was principally due to their lower general corrosion and oxidation rates compared to carbon steels in oxidizing atmospheres and aqueous solutions. We recognized the difficulty in welding these materials (high degree of martensite formation) because of the high carbon contents in the usual commercially available material. Like the parallel work going on in the salt repository program, we were giving some consideration to using a titanium-clad, carbon-steel container. However, we did only a cursory amount of testing on titanium.

We began some corrosion testing of 304L stainless steel in December 1982. At that time it was a fair certainty that this material would be used for glass pour canisters, so it was logical to include it in the testing activity. Corrosion testing activities were underway at LLNL and

through sub-contract to Battelle's Pacific Northwest Laboratory (PNL). The work sponsored at PNL was concerned mainly with the corrosion rates of irradiated specimens of carbon and alloy steels, since PNL had a gamma pit facility available for this kind of testing.

The considerations that served as the bases for the choice of container materials, designs, and testing activities were completely modified during the "Orange write-in" in the early spring of 1983. The work on ferrous materials was not completely terminated, however, since carbon steel remained as the principal choice for a borehole liner material (see Section 3.4).

3.2 "Orange" Draft of Site Characterization and Selection of a "Reference Material"

NNWSI Project managers and principal investigators convened to write a "Site Characterization Report" (SCR) in February 1983. By this time, the Topopah Spring tuff member had been selected as the stratigraphic location for the repository horizon. This layer was well above the water table at the site where the repository would be excavated. As explained in Section 2.3, location of the repository in this horizon opened the way to consideration of thin-walled containers, and this was a significant departure from previous design activities on waste packages. Along with the thin-walled container design was the importance of corrosion and oxidation resistance in what were viewed as dominantly oxidizing conditions. This set the stage for selection of Type 304L austenitic stainless steel as the reference container material for the NNWSI waste package designs.

In composing the Orange draft of the SCR, there was a need to specify "reference" conditions

and components. Among these were the reference container material, the reference design for each kind of waste package (with regard to dimensions, internal configuration, and power load), the reference emplacement orientation, the reference areal power load for arranging the containers in the repository, the reference groundwater, and so on. The purpose for specifying these "references" was to establish some common elements across the Project so that the different activities could be conducted in parallel with these common elements as reference points. In many of the activities, one or more "alternatives" were being studied along with the "reference" condition or component.

Selection of 304L as a reference material for the "Orange" draft was based on anticipated oxidizing but not especially aggressive environmental conditions at the Yucca Mountain repository. This material is readily fabricated and welded by many different processes. The material possesses a high degree of fracture toughness and has excellent mechanical properties. The L-grade (low carbon) was specified because of its greater resistance to developing "sensitized" (chromium depleted) microstructures in the grain boundary regions following the welding operation. Type 304 stainless steel, and its various modifications including the low carbon grades, are "workhorse" materials for many industrial applications; therefore, a large database exists on the performance of these materials in a wide variety of natural and chemical environments. The kinds of environments that were expected to dominate at Yucca Mountain were water vapor and atmospheric gases at temperatures up to about 250 C during the early part of the containment period. Then, gradually decreasing temperatures and increasing probabilities of wet conditions would occur in the late part of the containment period as the 96 C isotherm gradually moved toward the waste package container surface. The time when the 96°C isotherm arrived at the container surface would depend heavily on the type of waste, characteristic of the waste, rock parameters, and several design parameters of the waste package and repository. Wet conditions could develop around the container once the temperature cooled to or below 96 C and vadose water was present in the near-package environment.

The reference groundwater, associated with the Topopah Spring member, and derived from Well J-13 on the Nevada Test Site, is near neutral pH, low in salinity (appx. 7 ppm chloride ion), and oxidizing (appx. 5 ppm dissolved oxygen and

appx. 10 ppm nitrate ion). The environmental conditions were generally held to be comparatively non-aggressive (particularly when compared to environmental conditions in the other geological repository sites). This was based on three assessments: [see ref 5 and ref 7] (1) the vadose water would evaporate before it entered the near-package environment, (2) the small downward flux of water meant that when the temperature cooled below the boiling point only a small amount of water would contact the container surface and remain for a rather short period of time, and (3) *non-irradiated* water of the J-13 type of composition was not especially damaging to stainless steels. Given the concurrent radioactive decay and thermal decay, the view was that the container would unlikely be simultaneously exposed to aqueous conditions and a significant gamma field to effect radiolytic chemical changes in the environment. Given these thermal and environmental conditions, the performance of the stainless steels was believed to be adequate in meeting the substantially complete containment objectives of the waste package.

The leading defense waste form producer (Savannah River) proposed to pour the glass into 304L stainless steel canisters, and this was a factor in making this material the choice for the reference material. At the time of the Orange draft, the NNWSI Project was considering using the pour canister as the disposal container for the vitrified waste form packages. The Project later decided to "overpack" the pour canister into a disposal container (late 1984), so that later versions of the SCP and other project documents reflect this difference in configuration.

The limitations on 304L stainless steel were recognized very early on and were discussed in the section on metal barrier materials written for the Orange draft of the SCR. The advantages of other grades of stainless steels and stainless alloys with higher amounts of nickel, chromium, and molybdenum were discussed in terms of improved resistance to different forms of localized corrosion and stress corrosion cracking. Although low temperature oxidation was viewed as the dominant degradation mode with respect to time in the repository, the various modes of aqueous corrosion were viewed as more likely to limit the containment performance of the container material if and when an aqueous environment intruded into the vicinity of the waste package container.

While the final version of the entire Orange draft was never issued, parts of it were published elsewhere in topical reports and conference

papers. Much of the text of the metal barrier section was published in two conference papers prepared in the autumn of 1983 (MRS, December 1983, [ref 8] and NACE, March 1984 [ref 5]).

It is important to note that in 1983, the three repository projects (salt, basalt, and tuff) were engaged in project concurrence (and occasional informal competition) on completing site characterization planning work along with other baseline documents (Mission Plan, Environmental Assessment of each site). One special advantage that the Yucca Mountain site offered was its repository location above the water table. Another advantage proposed by the NNWSI Project was to use the reprocessed waste packages in the "as produced" condition, as discussed in the next section. It was felt that the NNWSI waste package could be designed cost-effectively with less repository excavation and less costly handling operations, and by using moderately corrosion resistant and moderately priced container materials.

3.3 Use of Bare Pour Canisters for Containment

In the "Orange draft" it was proposed that the pour canister to be used for the defense high level waste (DHLW) also act as the containment vessel for disposal. That is, there would be just one metal barrier, and it would be the same vessel into which the borosilicate glass was poured. In 1983, the Savannah River plant was advancing the process it had developed for making DHLW. The Savannah River operation called for pouring the molten glass into Type 304L stainless steel pour canisters (appx. 61 cm OD by 300 cm high with a wall thickness of 1 cm.) In the Savannah River process, the molten glass left the melter at a temperature of around 1050 C and was poured very slowly into the stainless steel vessel. About 17 hours were required to complete the pour; during the operation, surface peak temperatures of 550-700 C were recorded on the canister surface. After filling, the canister was closed by an upset resistance weld process. In the process, a high current was passed between the canister and a tapered plug (appx. 13 cm in diameter) that was simultaneously pressed into the canister opening to fuse them together. The chief reason for selecting 304L stainless steel for the pour canister was its excellent oxidation resistance; the entire process is to be carried out under atmospheric conditions, and little radioactively

contaminated scale develops on the stainless steel canister surface.

In 1983 it was not clear whether defense waste would go into the repository. According to the Nuclear Waste Policy Act of 1982, the President would make that decision. (He did in the spring of 1985). Because spent fuel was the primary and most radioactive waste destined for a commercial repository, less concern was raised about the defense waste. There was justification that if the defense waste could be used "as is" (that is, in its own pour canister) without any further process operations at the repository site, then a major cost savings would be achieved. Also, use of the bare pour canisters would only be feasible at the Yucca Mountain repository because of the lack of external pressure. This would result in a further economic advantage of the site.

However, the direct use of the "bare" pour canisters raised an important technical issue about the metallurgical condition of the canister. Because of the time-temperature-strain history of both the glass pouring operation and the upset resistance weld operation, portions of the canister (especially at the bottom where the temperature remained the highest for the longest period of time and the heat-affected-zone around the highly strained upset resistance weld) were apt to become sensitized during these operations. It also appeared that the canister wall would be in hoop tension because of the differential thermal contraction of the glass and metal upon cooling.

While it may have been possible to prevent sensitization by careful control of the alloy composition and the process history, this would have required such a considerable amount of process control by the operator that it appeared impractical to continue to consider the "bare" defense waste pour canister as the disposal container. Also, there was the point (and a report written on the subject - ref 22) that even if the microstructure was not discernibly sensitized during the high temperature processes (glass pouring, welding), carbide nuclei would form in highly strained areas and that portions of the canister could eventually be sensitized over a longer period of time at lower temperatures (low temperature sensitization phenomenon). A letter was written in the autumn of 1984 from L. D. Ramspott (LLNL Technical Project Officer) to D. L. Vieth (then NNWSI Project Director at DOE) recommending that the defense waste pour canisters be "over-packed" in another metal barrier. This outer metal container would then function as the dis-

posal container. This letter is appended as Attachment B.

The timing of this letter should be noted because reports written before the summer of 1984 considered the pour canister as the disposal container, and thus there was a great deal of emphasis on sensitization concerns in these reports. At that time, the NNWSI Project was focusing its materials effort on low carbon austenitic stainless steels. Sensitization of the stainless steels was a major concern because the canister would lose its "stainless" quality around the grain boundaries where the chromium content was depleted. The resulting material would then be very susceptible to a form of localized corrosion (intergranular corrosion) and to a form of stress corrosion cracking (intergranular SCC) because of the chromium depletion. Thus, the as-fabricated and filled pour canister would go into the disposal site in a corrosion susceptible condition.

Cast Irons:	
Gray Cast Iron	Nodular Cast Iron
Carbon Steels:	
AISI 1020	A537
Alloy Steels:	
9 Cr-1 Mo	
Ferritic Stainless Steels:	
AISI 409	430
26 Cr-1 Mo	29 Cr-4 Mo
Austenitic Stainless Steels:	
AISI 304L	304 ELC
316L	317L
321	AL 6X
Alloy 20 Cb3	JS 700
Nitronic 33	
Duplex Stainless Steels:	
Ferrallium 255	
Nickel-Based Alloys (alloyed principally with Cr, Mo, Fe):	
Alloy 825	Alloy G-3
Alloy 625	Alloy C-276
Nickel Based Alloys (alloyed with Cu):	
Alloy 400	
Titanium and dilute alloys:	
Ti-Grade 2	Ti-Grade 12
Zirconium and dilute alloys:	
Zr 702	Zircaloy(reactor grade)
Copper and Copper-Base Alloys:	
Electrolytic Tough Pitch Copper (CDA 110)	
90/10 Copper-Nickel (CDA 706)	
70/30 Copper-Nickel (CDA 715)	
Table 1 - Initial list of materials considered in 1983 survey (31 metals and alloys).	

3.4 1983 Survey of Container Materials

In the last months of 1982, we began a survey of candidate materials that would be practical for consideration in the site-specific NNWSI designs being developed in this same time period. Work on this survey was intensified in the spring of 1983 (concurrent with the Orange write-in) and drafts of the survey circulated in April-May 1983 with considerable revision occurring during the summer of 1983. The survey was finally published in October 1983. [Russell, et al, ref 4] For simplicity, we will refer to this as the 1983 Survey.

Initially, the survey considered some 31 engineering metals and alloys. Virtually all of the important alloy systems were represented, the major exceptions being aluminum-based alloys (not considered because of their low melting points) and high strength steels and nickel-based superalloys (not considered because of modest strength requirements for waste package containers). Listed according to compositional and structural classifications, the 31 candidates on the original long list are given in Table 1.

The above list represented a broad cross-section of metals and alloys. The list was derived from metals and alloys being considered by other repository projects or those that were discussed in publications pertaining to nuclear waste containment. One document that was especially useful was the report by Nuttall and Urbanic [ref 9] from the Canadian AECL. This report discussed, in rather general terms, the good and bad points of the important alloy families with regard to possible long-term degradation modes. Also, discussion with manufacturers and technical colleagues enlarged the list, often to include materials that are relatively new and that have been developed for improved corrosion resistance and better mechanical properties. Note also that plans for testing many of these same materials had been made in the summer of 1982, while multiple locations for the repository horizon were still under consideration [Attachment C]. The materials were initially evaluated in terms of four major criteria: (1) cost, (2) mechanical properties, (3) corrosion resistance, and (4) weldability. Each of these four areas was further broken down into a list of factors that could be comparatively evaluated.

This initial long list of 31 candidates was then shortened to a list of 17 candidates. A quantitative figure-of-merit approach was used to compare these candidates. As a result of this ap-

proach, 4 metallic materials were then selected for the testing program. The list of 17 candidates is the one discussed in the paper by Russell, et al. [ref 4], according to the above four general criteria. There was no formal documentation on how the list of 31 was reduced, but personal recall from that period of time can explain some of the eliminations.

Many of the alloys on the longer list (31 candidates) were quite similar to one another, and this was the major reason why some were eliminated early on (e.g. JS 700 vs. AL 6X among the high-nickel, high-molybdenum austenitic stainless steels, C-276 vs 625 among the high-performance nickel-base alloys, G-3 vs 825 among the intermediate nickel-base alloys, 29 Cr - 4 Mo vs 26 Cr - 1 Mo among the low-interstitial, high-performance ferritic stainless steels). In other cases, problems of fabricability or weldability prevailed in the initial screening (e.g. elimination of cast materials and difficult-to-weld high-carbon alloy steels). In still other cases, the initial evaluation criteria were severe, and candidates were eliminated because it seemed their performance under the environmental conditions was not adequate. This was the case with copper and some of its alloys, where our initial judgment was that these materials would have high corrosion rates in oxidizing, irradiated environments. We were later asked by the Department of Energy to reconsider copper (beginning of FY-85). When we did some actual testing on copper under irradiated environmen-

tal conditions, the corrosion rates were not nearly as high as expected, with the result that copper and some of its alloys were later added back to the candidate list. This is explained in much more detail in the next section (3.5).

The 17 candidates remaining on the second list are given in Table 2. The process used for reducing the container candidate list from 17 to 4 is explained in the Russell et al paper [ref 4]. However, there are some important remarks that need to be made in understanding this process. As a convenience to the reader, selected tables from the 1983 Russell report are provided in Attachment D. Points of interest in the 1983 survey are:

A. The 1983 Survey considered the four evaluation areas (corrosion resistance, mechanical properties, weldability, and cost) as equally important. In this survey only the cost of the manufactured product (\$/cubic inch of material) was considered (Table 7 of the Russell et al report). Costs involved in handling and in closing the containers in the hot cell facility, including documentation of the material and process for quality assurance and quality control, will likely dominate over the cost differences between the candidate materials. Thus, the total cost of the waste package rather than the price per cubic inch now is a deciding factor among the candidate materials.

B. With regard to mechanical properties, the 1983 survey emphasized the importance of the nil ductility temperature and the high-temperature yield strength (Table 8 in the Russell et al report), because these properties were related to design requirements at that time. In 1983, one consideration for the container material was that it would have sufficient resistance to "survive a fire test" such that a filled container would withstand a half hour at 800 C without rupture. Hence, the mechanical strength of the container at elevated temperature was important. At somewhat the other extreme, importance was attached in 1983 to the low temperature mechanical properties because of possible exposure to low ambient temperatures during movement from the surface facility to the underground emplacement on the "coldest day" possible in the climate of this region of Nevada. [Hence, emphasis on mechanical properties at -18 C or appx. 0 F, where there is a body of information in the literature.] Table 8 in the Russell et al report gives some figures on the fracture toughness minimum at -18 C and the nil ductility temperature (often around -18 C for the more easily embrittled materials). With regard to mechanical properties, the waste package

Carbon Steels:

AISI 1020 A537

Ferritic Stainless Steels:

AISI 409 26 Cr-1 Mo

Austenitic Stainless Steels:

AISI 304L 316L

317L 321

JS 700 Nitronic 33

Duplex Stainless Steels:

Ferralium 255

Nickel-Based Alloys (alloyed principally with Cr, Mo, Fe):

Alloy 825 Alloy 625

Titanium and Dilute Alloys:

Ti-Grade 2 Ti-Grade 12

Zirconium and Dilute Alloys:

Zr 702

Copper and Copper-Based Alloys:

70/30 Copper-Nickel (CDA 715)

Table 2 - Second list of materials considered in the 1983 survey (17 metals and alloys).

design requirements and desirable design features that were utilized in the 1983 survey are listed in Attachment G (taken from Table 1 of Reference 6).

C. The weldability parameters, expressed in Table 9 of the Russell et al report, were assessed in a binary fashion (0 = no special problems, 1 = special problems) with no intermediate responses permitted. This was done because evaluating weldability, per se, is a complex issue. The authors of the paper contacted several experts on welding, and the results in the table are a compilation of their opinions. Since the time of the 1983 survey, the Design, Fabrication, and Prototype Testing Task has undertaken a more thorough study on evaluating different welding processes. [refs 10, 11]. The 1983 survey was limited to the more conventional types of fusion welding processes; e.g., gas-metal-arc (GMA), gas-tungsten-arc (GTA), shielded metal arc (SMA) weld processes. Both filler and autogenous processes were considered for the GTA weld. In the more recent study, [Refs. 10, 11] performed by Babcock & Wilcox (B&W), more "state of the art" processes were considered (e.g. electron beam, friction welding, plasma arc welding). This is especially important for some of the "newer" metals and alloys, where difficulties are sometimes encountered in using the more conventional processes.

D. The corrosion and oxidation rate data, given in Table 5 of the Russell et al report, were an attempt to express rather complex phenomena in a simple tabular form. Virtually every one of the tabular entries is a compromise, with several important qualifications. This information was supplied with no experimental knowledge of the corrosion response of most of the metals on the list to J-13 well water, which was the reference groundwater for the repository. Some testing of carbon steel and other ferrous alloys had begun in the summer of 1982; but no test data on the stainless steels, nickel-base, copper-base, or titanium-base alloys had been obtained in early 1983.

Table 5 of the Russell et al report lists first the maximum oxidation rate for the candidate materials in steam and in moist air. Temperature was not specified, because the oxidation rate was not expected to vary appreciably over the relevant temperature range. Each of the major categories of aqueous corrosion was identified with a "maximum rate" and a "probability" term in Table 5 of the Russell et al report. The reason why this table was organized in this manner was an attempt at an early analysis of degradation

modes that would affect the container material once aqueous conditions could occur on the container surface. The probabilities of all the aqueous corrosion degradation modes added to one. The "probability" term was a compilation to describe the population of containers affected by the particular corrosion degradation mode, and the time during which the mode would operate. With regard to the localized corrosion and environmentally accelerated cracking, the probability term tacitly incorporated the individual probabilities that the "right" conditions with respect to the ionic concentration, solution pH, solution E_h , susceptible metallurgical structure, crevice size, stress intensity, and so on, were all simultaneously met.

As explained in the Russell et al report the various terms in the more detailed tables for (1) corrosion resistance, (2) mechanical properties, (3) weldability, and (4) cost were scaled down to a system of three tiers. The single figures assigned for the tiers were 0 = some disadvantages, 1 = suitable, and 2 = superior. The scores from the four columns were totaled (eight would have been a "perfect score") and compared. Then the materials were ranked. The "top scores" were obtained by 304L, 316L, and 321 stainless steels and alloy 825 (a nickel-base alloy closely related to the stainless steels and sometimes described as a stainless alloy). These four materials were recommended as candidates for the NNWSI Project container designs.

AISI 1020 carbon steel, which did not fare too badly in the analysis, was recommended as the candidate material for NNWSI Project design borehole liners. No other borehole liner candidate materials were named.

The NNWSI Project testing activities went into "high gear" beginning in March 1983 (while the "Orange" draft of the SCR was being written and while the 1983 survey was proceeding) and into the summer of 1983. This will be discussed further in Section 3.6. As a result of the Orange draft of the SCR, the Project now had its "reference material" and three alternatives (all austenitic materials). The alternatives were similar enough (strength, ductility, toughness, and principal alloying elements - Fe, Cr, Ni) to the reference material, that activities involving the waste package design, repository design, interactions with the waste form, and interactions with the environment could all proceed in parallel. This was the intention of the Orange convocation and the Project plan developed at that time. These same corrosion-related issues (the principal difference among the candidate alloys) were

explained in the paper presented at the 1984 NACE Conference [ref 5]. This paper also contained some of the first repository relevant experimental information on these materials.

More recently, as discussed in the Scientific Investigation Plan (SIP) for the Metal Barrier Task, a more detailed and quantitative system is being developed for selecting the candidate material(s) for advanced design work. Similarly, the Design Task is pursuing activities to select processes for fabricating, welding, and inspecting the container. A third task is concerned with study of alternate materials and designs. Initially, this task is examining a wide variety of materials (metals and non-metals), including re-examining some of the materials in the "long list" of the 1983 Survey. The interaction of these tasks and plans for the near future are discussed in Section 4.0.

3.5 Copper Container Feasibility Study

The BWIP and NNWSI Projects were formally requested in the early part of 1984 to give consideration to copper and copper-base alloys in their waste package container studies and to develop plans for formally addressing the feasibility of copper. This feasibility study was to be a two-year (FY-85 and FY-86) activity. The reason given for undertaking the copper feasibility study was at the request of members from both Houses of Congress. It was felt that copper (or one of its alloys) could be shown to be a viable container material in one of the repository programs. The Salt Repository Project Office (SRPO) - successor to ONWI - was not asked to participate.

Two NNWSI Project reports were written on the status of the feasibility study at the end of each fiscal year (FY-85 and FY-86). These are cited as references to consult for additional details on this study [refs 13, 14]. These reports were extensively reviewed by the Project management and DOE/HQ before release. The plan for the feasibility evaluation, as well as the two year-end reports, were reviewed by a two-member peer review panel for completeness of the evaluation.

In Attachment E, the list of initial concerns with copper are presented, as well as a general plan formulated in May of 1984 for evaluating copper. In early May 1984, we (L. B. Ballou, then Task Leader for the Waste Package and the writer) met with the WMPO Director (then D. L.

Vieth) to outline the strategy we would take in meeting the DOE request. It was agreed that NNWSI would actively undertake the feasibility study and that we would enlist the help of two copper industry technical organizations, the Copper Development Association (CDA) and the International Copper Research Association (INCRA) in performing these feasibility studies. Contacts were made with W. S. Lyman of CDA and D. Peters of INCRA.

One of the first items requested from the copper industry was their assessment of which grades of copper and copper-base alloys should be included in the feasibility study, given the thermal, radiation, chemical, and mechanical conditions of the expected environment at the Yucca Mountain repository. Their reply was that we should consider five materials: (1) oxygen-free copper, UNS C10200; (2) a 7% aluminum bronze alloy, UNS C61300; (3) 70/30 copper-nickel, UNS C71500; (4) beryllium copper, UNS C17200; and (5) MZC copper, an oxygen-free copper containing small additions of Mg, Zr, and Cr, UNS C18100. These materials are described in the letter from W. Stuart Lyman (June 15, 1984) and copied in Attachment F. Detailed reasons for the recommendations of these five materials are cited in the letter.

The reasons for selecting the first three materials as candidate container materials remain as valid today as they were in 1984. The aluminum bronze was selected as a candidate because of its excellent oxidation resistance; the 70/30 copper-nickel was cited for its resistance to most forms of aqueous corrosion, including (for a copper-base material) some resistance to stress corrosion cracking in ammoniacal solutions. The oxygen-free grade of copper was chosen largely because of its role in the Swedish program. In that program, a massive container was proposed to be hot isostatically pressed from a copper shell onto a mass of powdered copper. The high-purity and oxygen-free grade was specified there in order to assure good bonding.

The last two materials, beryllium copper and MZC copper, were included primarily for their high strength at elevated temperature. In 1984, the NNWSI Project was still considering using the glass pour canister as the disposal container for the vitrified waste forms. The NNWSI Project wanted to explore the option that it could persuade the waste form producer to use a copper-base vessel, as well as any of the austenitic stainless steels or alloys. As events later turned out, the NNWSI Project abandoned the idea of using the bare glass pour canister as the disposal con-

tainer, and the leading defense waste form producer was well established in its choice of canister material and process (and would probably not accept a radical change in either). Thus, the need for a high-strength copper-base material was no longer present, and the feasibility evaluation centered on the first three materials listed. This is explained further in the FY-85 copper feasibility report [ref 13].

The addition of the copper-based materials offered new breadth to the NNWSI Project testing activities. Some of the criticism attached to having all of the candidates come from one alloy family was alleviated. We entered into a sub-contract agreement with CDA in which they supplied compilations of existing information on the copper and copper alloy candidate materials, such as mechanical properties over the temperature range of interest, corrosion and oxidation resistance in environments of interest, industrial processes for producing, fabricating and welding copper in workpiece dimensions of a nuclear waste container, and copper availability and price forecasts up to the 21st century. These were subjects that were to be addressed in the copper feasibility reports.

CDA and INCRA organized a task group on nuclear waste containers; this task group was comprised of people in the copper industry. This was one of the highlights of activities in the Metal Barrier Task for the opportunity it afforded in meeting with industrially oriented people and drawing on their talents and experience in developing plans for evaluating, testing, and selecting materials and processes for producing waste package containers. Several of the people on the Copper Waste Container Task Group were contributors to the reports prepared by CDA and used by the Metal Barrier Task staff in preparing the two feasibility reports on copper. We are currently planning to issue these reports as a source of detailed background information on copper and its alloys [ref 15]. We met formally two times with the Copper Waste Container Task Group (November 1984 and August 1985) in New York City. Smaller meetings, primarily with Stuart Lyman, Dale Peters, and Konrad Kundig, were held at LLNL in the 1984-86 period.

As part of the work with CDA and INCRA, we held a two-day workshop on copper and copper alloy containers in March 1986. The workshop was held in Houston TX. Participants from the copper industry, the NNWSI and BWIP Projects, the US DOE and subcontractors, and representatives from the nuclear waste programs in Sweden and Canada attended the workshop.

Both the Swedish and Canadian programs have emphasized copper as a container material in their package designs. A summary of the workshop was written; we are in the process of releasing this summary as part of the CDA compilations through the NNWSI publication procedure [ref 15].

Experimental studies to evaluate the recommended copper and copper alloys under conditions relevant to Yucca Mountain were undertaken by the Metal Barrier Task, beginning officially in October 1984. Actually, some testing was already underway at LLNL in the late spring of 1984 when the request for doing the copper feasibility study was first announced. This work involved corrosion testing in non-irradiated Well J-13 water. Sub-contract work was begun with Westinghouse Hanford Engineering Development Laboratory (HEDL) in the late fall of 1984 to perform corrosion testing in Well J-13 water and water vapor in a strong radiation field. Flat coupons for weight loss testing, creviced specimens, and welded U-bend types of stressed specimens were tested. We believed that the irradiated conditions would develop the most severe environments for general, localized, and stress corrosion testing. Environments, temperatures, and radiation dose levels were chosen to favor the formation of damaging species and result in "severe" test conditions.

The initial analysis of performance issues for copper and its alloys was concerned with the formation of additional oxidizing species and the formation of certain nitrogen-bearing compounds (refer to Attachment E). These are discussed in more detail in the two published feasibility reports, but it will suffice here to say that irradiation of atmospheric gases, water vapor, and water (in contact with atmospheric gases) could lead to production of ammonia, the various oxides of nitrogen, nitric acid, and hydrogen peroxide as well as several short-lived highly reactive radicals. While these same species could form in the environments around stainless steel and nickel-base alloys, these species would not be particularly damaging to these materials unless perhaps they were sensitized because of some prior thermal/mechanical treatment. In the case of copper, there was some concern that "runaway" corrosion conditions might occur if high concentrations of these species were present.

As the experimental activities later revealed, the oxidation and corrosion performance of copper was not catastrophic under the irradiated conditions and with the temperatures and environments used. (Not all expected combinations

of temperature and radiation doses were tested). Thus, copper and the two alloys looked promising as candidate container materials. The two-year feasibility study concluded that the three copper-based materials should remain as candidates in the NNWSI Project.

Another important point made in discussing the advantages of copper and the candidate copper base alloys vis-à-vis the multiple component stainless steels and alloys was the microstructural simplicity of copper (pure metal) and the copper-nickel alloy (essentially a binary solid solution). As an alternative alloy system, it was pointed out that the species which would be particularly damaging to the stainless types of material were not especially harmful to copper-base materials, and vice versa. On the other hand, the very low yield strength of high-purity copper would likely require a thicker container than the one-cm thickness specified in the reference design. Also, some concern was raised about possible ductility minima in copper in the range of the peak surface temperature on spent fuel package containers.

3.6 Experimental Activities (1982-86)

Although most details of the experimental work are beyond the scope and intent of this paper, some narration of the sequence of experimental activities does help in understanding the container material selection process. In the 1982 to early 1983 period (before the Orange draft of the SCR), laboratory work was concerned primarily with ferrous materials (cast irons, mild steels, alloy steels) with a token effort on titanium. Some thought had been given to expanding the list of materials (the 1983 plan given in Attachment C), and the survey of candidate materials was being planned. Sub-contract work began at PNL on general corrosion and stress corrosion work in the gamma radiation pit there. When the emphasis on container material changed direction to stainless steels following the Orange draft and 1983 survey, some testing of carbon steels continued, as the material was now considered as the prime candidate for the borehole liner. Some of the results of this work have been published [ref 18].

Beginning in 1983, the emphasis changed to the four container materials recommended by the Russell et al report [ref 4]. Weight loss coupon tests to determine the general aqueous corrosion rates (and to observe any localized corrosion ten-

dencies, since creviced washers were used) were begun on these materials. The weight loss tests were conducted in Well J-13 water at different temperatures in the 50-100°C range and in 100°C saturated steam. Later, tests in 150°C unsaturated water vapor (atmospheric pressure) were added. Stress corrosion cracking (SCC) tests in 100C Well J-13 water and wet vapor were commenced using four-point load bent-beam specimens. Some of these specimens contained welds, and others had various histories of heat treatment and cold work. The purpose of these metallurgical treatments was to establish differences in microstructure and to intentionally sensitize (partially or completely) the material. These bent-beam SCC susceptibility tests were confined to 304L and 316L (and some higher carbon 304) stainless steels, and the intent was to determine the susceptibility of these materials and conditions to intergranular (IG) SCC under the mildly oxidizing environmental conditions in the Well J-13 water and vapor. The "bare pour canister" was being pursued as the disposal container for glass waste forms at this time. Work at PNL was also oriented toward IGSCC susceptibility. Some stressed U-bends of 304 and 304L stainless steels were exposed to high radiation doses in the PNL gamma pit. Well J-13 water and the water vapor derived from it (at 50 and 90°C) were the test environments. Additionally, PNL performed some slow strain rate tests on 304, 304L and 316L stainless steel in non-irradiated environments and some U-bend tests on 304 and 304L under alternating wet-dry conditions in an autoclave.

As expected, the more highly susceptible materials/conditions (e.g. sensitized 304) cracked intergranularly in the irradiated environments. Specimens were more susceptible to IGSCC at the higher test temperature (90°C) than at the lower (50°C). Eventually, some of the 304L specimens cracked, but they cracked transgranularly. The reason for this change in crack morphology appeared to be an increase in the chloride ion content of the water, coupled with the oxidizing characteristics of the gamma irradiated environment. These experimental results are discussed in references 12 and 16. Bent-beam stress corrosion test specimens did not crack in any of the metallurgical conditions tested. In these cases the lower stress level (below yield stress) and less severe environmental conditions (no gamma radiation) created much less aggressive conditions. These results are discussed in reference 12.

This emphasis on stress corrosion testing of 304L was intended to define the limitations of this material, because it was believed to be the most susceptible of the four candidates to both IGSCC and TGSCC.

Localized corrosion testing of the austenitic candidate materials revealed (as expected) that the more highly alloyed materials were more resistant than the leaner materials [ref 19]. Crevice corrosion testing of 304L and 316L indicated that the "cleanliness" (primarily, fewer inclusions) of the material was important in promoting resistance to this form of corrosion in aggressive solutions. Gamma radiation caused a shift in the electrochemical corrosion potential to more noble values [ref 12]. In unmodified Well J-13 water, gamma radiation did not change the relative positions of the "pitting potential" and the "corrosion potential", but in 100x the solute concentration of Well J-13 water the positions were significantly changed. The prediction was that in the more concentrated electrolyte and under gamma irradiation, even the 316L material would pit [ref 20].

Experimental work on copper and copper-base alloys began in mid 1984. In parallel with the work on the austenitic materials, weight loss coupon tests in non-irradiated Well J-13 water were conducted. Testing under highly irradiated conditions (to establish a severe environment; rationale discussed in Section 3.5) was begun at Westinghouse HEDL on the three candidate materials in Well J-13 water and vapor. Results of this work have been presented in refs. 13, 14, and 21. The general statement of results was that the copper-base materials did not oxidize or corrode at an excessive rate under the strongly oxidizing conditions as was initially expected. Corrosion/oxidation rates under comparable irradiated and non-irradiated conditions are presented in ref 12 (Section 10). Perhaps, part of the reason why only a modest increase occurred in the irradiated rate (in aqueous environments) on unalloyed copper is that hydrogen peroxide forms, but catalytically decomposes on the copper surface. The catalytic decomposition is less effective on the alloys, and the ratio of the irradiated corrosion rate to the non-irradiated rate is much greater (Table 16 of Ref 12).

More description and details of observation of the irradiated copper and copper-base alloy tests are discussed in the report by Yunker [ref 21]. The information in this report is being updated with additional observations and measurements on the exposed specimens; however, the same types of results are expected. It is sig-

nificant to note that no SCC occurred on any of these specimens, despite environmental conditions selected to attempt to form aggressive nitrogen-bearing species (from radiolysis of water and nitrogen in the atmosphere, plus some nitrate ion already present in the J-13 water). In many respects, the high-purity unalloyed copper appears to be the better behaving material (no observed inhomogeneities in corrosion attack and film formation). However, there are some greater practical difficulties that we presently perceive in closing high purity copper containers. All of these factors need to be weighed in the material selection process.

3.7 Impact of 1986 Events on the Metal Barrier Task

Several events occurred in 1986 that resulted in some change in direction in the Metal Barrier Task activities. This and the following year 1987 were primarily devoted to planning. In the summer of 1986, the NNWSI Project recommenced preparation of the Site Characterization Plan (SCP). This time, the SCP was brought to the state of a completed draft (released in January 1988). In order to better identify the Quality Assurance (QA) levels for each parcel of work, a Project-wide Stop Work Order (SWO) was issued in June 1986. This resulted in closing out the experimental activities in the Metal Barrier Task; some of these experimental activities had been running since early 1983, and all were brought to an orderly termination by the end of 1986. To lift the SWO each task had to prepare a Scientific Investigation Plan (SIP) for the work planned for the task. There was some overlap in the content of the two plans. These plans are available [ref 1, 2]. The pause in experimental work and the requirement for producing documented plans was an opportunity to re-examine the goals and direction of the Metal Barrier Task.

The draft of Chapter 7 of the SCP (including the Metal Barrier part in Section 7.4.2) was completed in the summer of 1986, with some minor modification and reworking performed in the first half of 1987. The draft SCP was extensively reviewed by DOE, its contractors, and by outside technical reviewers. The Issue 1.4 Resolution Strategy and its subsumed Information Needs in Chapter 8 of the SCP were drafted in the autumn of 1986. These, too, were extensively reviewed and revised in early 1987.

In preparing the SCP, it was decided that AISI 321 stainless steel could be eliminated as

one of the candidate materials. We had done relatively little testing on this material, but more importantly, this grade of stainless steel did not offer any particular advantage that could not be gained with one of the other candidate materials. Alloy 825, like 321, is "stabilized" with a titanium addition that preferentially forms TiC rather than the Cr-rich $M_{23}C_6$ type of carbide; this results in a material that is resistant to sensitization effects. In addition, alloy 825 offers substantial improvement to other forms of corrosion (pitting, crevice, TGSCC) over 321 stainless steel. Even 316L stainless steel has advantages over that of 321 (improved resistance to localized corrosion and comparable resistance to sensitization because of the low carbon level and molybdenum addition in 316L). Thus, the SCP prepared in 1986 lists three candidate austenitic materials rather than the four that resulted from the Russell et al 1983 survey [ref 4]. The same three copper-base material candidates that were discussed in the 1985 copper feasibility report [ref 13] remained. The terminology "reference alloy system" was used for the iron to nickel-base austenitic materials (see Attachment B) and "alternative alloy system" was used for the copper-base materials. Now there were equal numbers of candidates in the two alloy systems. These are the resulting six candidate materials listed in Section 1.1.

3.8 Variants on Candidate Materials

More recently, there are some indications that a "variant" on the choice of unalloyed copper might be more appropriate than the oxygen free grade, CDA 102. This grade was originally selected (see Section 3.5) to provide a link to the

Swedish program. However, quite different container fabrication methods are being considered in the two programs, and it now appears that a deoxidized grade of copper, such as phosphorus deoxidized CDA 122, may be a better choice. The P addition is about 0.04% in the CDA 122 grade; otherwise, the material contains no other intentional alloying elements. Use of the deoxidized grades avoids oxygen absorption during hot working and welding operations. Oxygen forms copper oxide inclusions in the pure metal that can result in embrittlement or formation of water vapor blisters if the metal is exposed to a hydrogen-containing environment. Hydrogen can be generated by radiolysis of water or water vapor or by the slow electrochemical decomposition of water during the containment period. On the other hand, the phosphorus deoxidized grade appears to be more susceptible to ammonia-induced stress corrosion cracking than the oxygen-free grade of copper. However, since ammonia generation does not appear to be a probable event in the repository, this factor seems less important. This question of which grade of unalloyed copper to use in the selection process will need to have quick resolution.

Variants of the more standard compositions have been considered and tested before in the Metal Barrier Task. Some work was performed with different LN and nuclear grades of 304 and 316 stainless steel. These materials had low carbon but were fortified with higher nitrogen contents. Also, in some of them there were low sulfur and phosphorus levels (and hence low inclusion count). These materials generally had better performance than the standard grades with regard to crevice corrosion resistance and resistance to IGSCC (and probably TGSCC, as well).

4.0 SUMMARY AND GENERAL PLANS

This paper has provided the history of how the Metal Barrier Selection and Testing Task, in conjunction with other tasks in the NNWSI Project, has acquired the present set of six candidate materials. These six candidate materials have been considered in the conceptual designs of the waste package and have been described in the NNWSI Site Characterization Plan (SCP), now published as a Consultation Draft. Three of the candidates are copper-base materials and three of the candidates are iron- to nickel-base materials with a predominant austenitic (fcc) structure. The history was annotated to il-

lustrate the important role of the candidate selection process on waste package and repository design issues, on demonstration of containment strategy, on development of the material testing and evaluation efforts, on planning for the selection process for advanced design work, and finally on planning the project milestones.

In the earliest part of the waste package design effort, multiple locations for a repository site at Yucca Mountain were under consideration (1981-82). Emphasis at that time was on designing a thick waste package for a repository located below the water table; radiation self-shielded

designs were considered. Inexpensive cast irons and steels were viewed as attractive candidate materials for thick containers to attenuate the radiation and to provide for a corrosion allowance. An alternative design was to use a thick steel container as reinforcement with an outer thin shell of titanium as a corrosion resistant barrier. The decision to locate the repository in the unsaturated zone changed the container design and material emphasis to one of using thin-walled containers and corrosion resistant container materials. Preparation of the "Orange draft" of the NNWSI Site Characterization Report in early 1983 required nomination of reference materials and conditions. Type 304L stainless steel was selected as the design reference material for the waste package container because of its excellent oxidation resistance, good combination of mechanical properties, wide availability, amenability to multiple fabrication and closure processes, and extensive industrial usage. A survey of 17 engineering metals and alloys reinforced the choice of 304L stainless steel and identified other grades of stainless steel (316L and 321) and a related nickel-base alloy (825) as alternative candidates. These alternatives have similar physical and mechanical properties to the reference material and are more resistant to various forms of localized corrosion and stress corrosion cracking in aggressive environments.

At the request of DOE/HQ, copper and copper-base alloys were reconsidered as container materials in 1984. Specific copper grades and alloys were identified as candidates; the copper producing industry was consulted through CDA and INCRA. These organizations recommended a list of candidate materials for the feasibility evaluation, and they provided important information on the properties of these candidates. In the following two years, these materials were extensively evaluated and tested. The results of the feasibility evaluation indicated that these materials merited further study, and the copper-base candidates were retained in the NNWSI Project. The copper-base materials introduced additional alternatives to the stainless steels and the nickel-base stainless material, because the

potential degradation modes and their causative conditions were quite different for the two classes of materials. Initially, there were five candidate coppers and copper alloys; later this list was reduced to three candidates (oxygen-free Cu, CDA 102; 7% aluminum bronze, CDA 613; and 70/30 copper nickel, CDA 715).

Candidates from the iron to nickel base austenitic materials (stainless steels and stainless alloys) and from the copper base system comprise those under consideration for metal barrier containers and discussed in the NNWSI SCP that was prepared in 1986-87. In preparing the SCP, Type 321 stainless steel was dropped as a candidate material because all of its advantages were shared by other austenitic candidate materials. Thus, there remain three copper-base materials (CDA 102, CDA 613, and CDA 715) and three iron- to nickel-base austenitic materials (AISI 304L, AISI 316L, and Alloy 825). The SCP has been currently released (1988) as a Consultation Draft. The SCP describes a plan for evaluating and selecting among these candidate materials for advanced design work.

Present and near-future efforts call for preparation of degradation mode surveys on the candidate materials and establishment of a plan for making the material selection based on a system of previously agreed upon selection criteria. The degradation mode surveys are now in draft form [ref 23], and a short version of one survey (on phase stability in the austenitic materials) has been published [ref 24]. Along with the experimental work specific to the Yucca Mountain site, these degradation mode surveys will provide important input to the selection process. The wider technical community will be consulted to help in making this selection. QA Level I testing and modeling activities on the selected container material will then be launched for acquisition of a defensible data base that will be presented as part of the license application. This data base will be obtained under environmental and metallurgical conditions that are meaningful to actual repository conditions and extrapolatable to repository time frames.

5.0 LIST OF REFERENCES

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2. "Site Characterization Plan, Consultation Draft, Yucca Mountain Site, Nevada Research and Development Area", U.S. Department of Energy, Office of Civilian Radioactive Waste Management, DOE/RW-0160 (January 1988) (see especially Sections 7.4.2 and 8.3.5.9)
3. Conceptual Waste Package Designs for Disposal of Nuclear Waste in Tuff, Westinghouse Electric Corporation Report AESD-TME-3138 (September 1982)
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9. "An Assessment of Materials for Nuclear Fuel Immobilization Containers", K. Nuttall and V. F. Urbanic, Atomic Energy of Canada, Ltd. report AECL-6440 (September 1981)
10. "Fabrication Development for High Level Nuclear Waste Containers for the Tuff Repository, Phase I Final Report", K. O. Stein, H. A. Domian, R. L. Holbrook, and D. F. LaCount, Babcock & Wilcox Nuclear Power Division, BAW-2010 (October 1987) (in review)
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12. "Progress Report on the Results of Testing Advanced Conceptual Design Metal Barrier Materials under Relevant Environmental Conditions for a Tuff Repository", R. D. McCright, W. G. Halsey, and R. A. Van Konynenburg, UCID 21044 (December 1987)
13. "FY-85 Status Report on Feasibility Assessment of Copper-Base Waste Package Materials in a Tuff Repository", R. D. McCright, UCID-20509 (September 1985)
14. "Feasibility Assessment of Copper-Based Waste Package Container Materials in Tuff Repository", C. F. Acton and R. D. McCright, UCID-20847 (August 1986)
15. "Background Studies in Support of a Feasibility Assessment on the Use of Copper-Base Materials for Nuclear Waste Packages in a Repository in Tuff", introduction by R. A. Van Konynenburg with appendices by K. J. A. Kundig, W. S. Lyman, M. Prager, J. R. Myers, and I. S. Servi (Copper Development Association and International Copper Research Association, Inc.), UCID- (May 1988) (in review).
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17. 10 CFR Part 60, "Disposal of High-Level Radioactive Wastes in Geologic Repositories; Licensing Procedures", U. S. Nuclear Regulatory Commission, (June 30, 1983) (see particularly sections 60.111 and 60.113)
18. "Corrosion Behavior of Carbon Steels under Tuff Repository Environmental Conditions", R. D. McCright and H. Weiss, Proceedings of the Materials Research Society Meeting, vol 44, pp. 287-294 (November 1984)
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24. "Impact of Phase Stability on the Corrosion Behavior of the Austenitic Candidate Materials for NNWSI", D. B. Bullen, G. E. Gdowski, and R. D. McCright, UCRL-97562 (October 1987)

6.0 LIST OF ATTACHMENTS

- A. Compositions of candidate materials, extracted from reference 12
- B. "Bare pour canister letter", Ramspott to Vieth (November 30, 1984)
- C. Excerpt from FY-83 test plan, McCright (July 8, 1982)
- D. Excerpt from Russell et al report, reference 4
- E. "Copper letter", Vieth to Stein (May 15, 1984) with attachment from McCright (May 9, 1984)
- F. "Letter recommending copper candidates", Lyman to McCright (June 15, 1984)
- G. Waste Package Design Requirements, excerpted from reference 6

NOTE ON ATTACHMENTS:

We have tried to provide the best available quality of document reproduction of the various attachments. Please note that the reproduction quality of attachments B, E, and F the attachment is poor due to unavailability of the original letters and their continued photocopying over subsequent years. Material in attachment C was retyped. Material in attachments A, D, and G is available in reports and widely distributed documents; these should be consulted for additional explanation and context.

— ATTACHMENT A —

Table 1. Alloy compositions for candidate container materials (austenitic alloys)^a.

Common alloy designation	UNS ^b designation	Chemical composition (wt.%)							
		C (max)	Mn (max)	P (max)	S (max)	Si (max)	Cr (range)	Ni (range)	Other element
304L	S30403	0.030	2.00	0.045	0.030	1.00	18.00-20.00	8.00-12.00	N: 0.10 max
316L	S31603	0.030	2.00	0.045	0.030	1.00	16.00-18.00	10.00-14.00	Mo: 2.00-3.00 N: 0.10 max
825	N08825	0.05	1.0	not specified	0.03	0.5	19.5-23.5	38.0-46.0	Mo: 2.5-3.5 Ti: 0.6-1.2 Cu: 1.5-3.0 Al: 0.2 max

^a Information adapted from ASTM specifications A 167 and B 424; refer to ASTM (1984).^b Unified Numbering System; refer to SAE (1977).**Table 2. Representative mechanical properties for candidate container materials (austenitic alloys)^a.**

	Tensile strength (min)		Yield strength (min)		Elongation (min)	Reduction of area (min)
	(MPa)	(psi)	(MPa)	(psi)	(%)	(%)
304L (annealed)	483	70,000	172	25,000	30	40
316L (annealed)	483	70,000	172	25,000	30	40
825 (annealed)	586	85,000	241	35,000	30	not specified

^a Information adapted from ASTM specifications A 167 and B 424; refer to ASTM (1984).

Table 3. Alloy compositions for candidate container materials (copper and copper-base alloys)^a.

Common alloy designation	UNS ^b designation	Chemical composition (wt.%)								
		Cu	Fe	Pb	Sn	Al	Mn	Ni	Zn	Other
CDA 102 (oxygen-free copper)	C10200	99.95 (min)	--	--	--	--	--	--	--	--
CDA 613 (aluminum bronze)	C61300	92.7 (nom)	3.5 (max)	--	0.2- 0.5	6.0- 8.0	0.5 (max)	0.5	--	--
CDA 715 (70-30 cupronickel)	C71500	69.5 (nom)	0.4- 0.7	0.5 (max)	--	--	1.0 (max)	29.0- 33.0	1.0 (max)	--

^a Compiled from CDA Standards Handbook Data Sheets, Copper Development Association, Greenwich, CT.

^b Unified Numbering System; refer to SAE (1977).

Table 4. Representative mechanical properties for candidate container materials (copper and copper-base alloys).

Common alloy designation/condition	Yield strength ^a (ksi)	Tensile strength (ksi)	Elongation (%)
CDA 102			
Hot rolled	10	34	45
Hard	45	50	4
CDA 613			
Soft anneal	40	80	40
Hard	58	85	35
CDA 715			
Hot rolled	20	55	45
Half hard	70	75	15

^a 0.5% extension under load. Compiled from CDA Standards Handbook Data Sheets, Copper Development Association, Greenwich, CT.

— ATTACHMENT B —



LAWRENCE LIVERMORE LABORATORY

NWM:LR 84-609

November 30, 1984

Dr. Donald L. Vieth, Director
U.S. Department of Energy
Waste Management Project Office
Nevada Operations Office
P.O. Box 14100
Las Vegas, NV 89114

SUBJECT: Follow-up to Waste Package Reference Design Change
Recommendation (Action Item 84-34)

REF: Letter Ramspott to Vieth (NWM:LR 84-294) 6 June 1984

Dear Don:

During the discussion of the reference letter at the June TPO meeting, you requested additional information on the recommended waste package reference design changes. Due to the press of other activities, this has not been addressed, and the delays in the SCP removed some of the urgency. However, I apologize for our tardiness.

Although in our June presentation we suggested a switch to 316L, we have subsequently decided to back away from a specific alloy as a "reference" containment barrier material until we are technically prepared to defend a recommendation for selection. This selection is a major milestone (M265) now scheduled for 9/30/87. Until that time and specifically for the EA and SCP, we plan to use the generic term "austenitic stainless steel" to describe the reference material, with "copper-based alloys" as the descriptor for the alternative material.

Aside from material cost-related considerations, no significant differences have been identified among the candidate stainless steels which would have a major impact on other project activities such as repository facility designs. Therefore, rather than committing to any particular alloy as a "reference" in the SCP, and trying to explain later why we changed our minds (if we did), we will be better off with the generic terms until we have accumulated the data base to support a specific alloy decision. The material testing program for the stainless steels is not affected by this position, as we have been testing several alloy candidates and will continue to do so. The copper alloy testing program is just now getting started, but will be vigorously pushed for the next two years to bring it to an information level where the viability of these materials can be objectively assessed.

You specifically requested an indication of the impacts on the EA and on funding of both the "reference" material change and the recommendation to abandon "bare" glass pour canisters as a containment barrier.

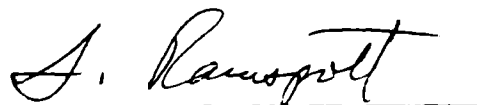
With respect to the EA, the only waste form discussed is spent fuel and therefore the glass pour canister issue is not important. The EA text reflects the "austenitic stainless steel" terminology except where specific reference is made to 304L corrosion data used in the extrapolation of containment time projections.

From the funding viewpoint, the addition of an overpack to the glass pour canisters has no significant effect on the material testing program supported by the Waste Fund. The geometry and assembly considerations are essentially the same as for spent fuel containers and will require equivalent repository facilities and equipment for closure welding, inspection, and handling. These overpacks are expected to cost ~\$8 K each. This will represent about \$2.5 M for the 300 canisters of West Valley glass. The cost to overpack the ~7000 canisters of DHLW glass, to be borne by Defense Programs, will be \$50-60 M and is significant. However, this is no more, and probably less, than they would cost in either BWIP or salt where thick carbon steel overpacks are planned.

As we indicated in the reference letter, we do not know how we can make a truly defensible case for use of bare pour canisters with the time-temperature history approaching sensitization conditions and the high residual stresses, at any price.

As indicated above, the stainless steel testing program, and its projected cost, are essentially unaffected by the generic material designation.

If further information on these topics is needed, please contact Lyn Ballou or me.



Lawrence Ramspott
LLNL Technical Project Officer
for NNWSI

LDR:LB:bb

cc: External

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— ATTACHMENT C —

(FY-83 Proposed Tasks)

Statements of Work
R. D. McCright

July 8, 1982

THREE METAL BARRIER TESTING AND SELECTION

3.1 Corrosion Testing and Evaluation

This task concerns the measurement of the corrosion penetration rate, the corrosion attack pattern, and determination of the corrosion rate laws which prevail under repository relevant environmental conditions. These conditions include steam and the native groundwaters plus modification to these environments which are induced by emplacement of the waste package. These modifications include thermally-induced changes in the environment, radiation-induced changes, as well as chemical changes induced by the corrosion products of the metal barriers. The task is divided into:

3.1.1 Corrosion of Irons and Steels as Overpack Materials

Conceptual designs specify cast irons as reference materials for the self-shielded overpack and steels for reinforcement in bore-hole overpack. Oxygen dissolved in the groundwater is expected to be the major limiting factor in the corrosion performance of irons and steels. The corrosion rate and rate laws are determined as a function of oxygen, temperature, pH and E_H . The presence of oxidizing species, such as those generated during radiolysis of the steam and groundwater may significantly influence the corrosion behavior of the bore-hole steel barrier. Alloying the cast iron or steel may be beneficial and its effect is determined. Long-term localized attack, particularly graphitization of cast iron is explored. Stress corrosion and hydrogen-induced cracking is addressed as a possible concern especially in the welded regions.

3.1.2 Corrosion of Titanium and Ti Alloys as Overpack Materials

Conceptual designs use titanium grade 12 as the reference materials for the outer shell in bore-hole overpacks. The corrosion performance of titanium alloys is surveyed under repository relevant conditions to determine possible failure modes of the thin shell. Corrosion in a radiated environment is determined. Galvanic corrosion effects between the titanium outer shell and steel reinforcement are surveyed and quantified, as a breach in the titanium may accelerate penetration into the steel. Environmentally accelerated stress corrosion cracking and hydride formation may significantly limit use of titanium.

Note: Because of the poor copy quality of the original version, this has been retyped.

3.1.3 Corrosion of Alternative Materials as Overpacks

As a high degree of corrosion performance is demanded of the outer shell, alternative materials to titanium are sought. These include nickel-base alloys, copper-base alloys, and high-nickel stainless steels. A survey of the corrosion performance of these materials is determined in repository relevant conditions. Radiolysis effects and galvanic coupling to steel are explored.

3.1.4 Corrosion of Canister Materials

While the canister is not primarily designed as a corrosion barrier, the corrosion performance of this material (presumably a 300 series stainless steel) is determined. An accident may breach the outer structural barriers.

3.1.5 Corrosion Mitigation Methods

The corrosion penetration rates of iron and steels may be reduced by incorporation of pH or E_H buffers in the backfill. Passive cathodic protection systems and oxygen getters may be useful as corrosion preventive measures.

3.2 Mechanical Properties and Evaluation

The overpack should possess certain minimal strength, ductility, and toughness requirements. This task defines these requirements and their influence on the corrosion screening and material selection processes.

3.2.1 Relevant Mechanical Properties of Overpack Materials

The relevant mechanical properties of the different candidate materials are defined and compiled over the temperature range of interest. Environmentally sensitive properties are identified. In particular, the lowering of the fracture toughness parameter, K_{IC} , for stress corrosion and hydrogen embrittlement susceptible materials is assessed. Long-term physical metallurgical, aging, and creep property changes are surveyed and evaluated in terms of their influence on mechanical properties and corrosion performance.

3.2.2 State of Stress Calculations

The state of stress is calculated on the outer package barrier and takes into account the lithostatic, hydrostatic, and thermal stresses (including any cyclical components), as well as the residual fabrication stresses and stresses in and around the welded region.

3.3 Fabricability of Candidate Materials

The scope of this task involves assessment of the fabricability of candidate materials which are acceptable from a corrosion resistance and a mechanical properties point of view. The task includes evaluation of the metallurgical processes used for fabricating the containers as well as the joining process for sealing the containers.

3.3.1 Any special problems created by the fabrication process and the effect on the mechanical and corrosion behavior is determined. The affect of imhomogeneities on the corrosion performance is assessed.

3.3.2 Welding Processes and Post-Weld Inspection

Welding procedures for the different candidate materials and designs are surveyed. The compositional changes around welds where filler materials are used are evaluated for their effect on corrosion performance and changes in mechanical properties. The heat input and resultant metallurgical, microstructural changes is determined for its effect on the compositional, stress, and corrosion behavior patterns. In particular the need for pre-weld and/or post-weld heat treatments for thick sections in the self-shielded design will be addressed.

— ATTACHMENT D —

Table 5. Estimated relative maximum corrosion rates for selection of candidate metals.^a (See Table 3 for reference corrosion environment.)

Material designation or composition	Steam (mpy)	Moist air condition (mpy)	Continuous air/water film								Stress corrosion cracking					
			Corrosion mechanisms, rates (mils/yr), ^b probabilities													
			General		Pitting		Crevice		Intergran.		Intergran.		Transgran		H ₂ embrit.	
			Rate	Prob.	Rate	Prob.	Rate	Prob.	Rate	Prob.	Rate	Prob.	Rate	Prob.	Rate	Prob.
AISI 1020 steel	0.05	2	8	0.2	30	0.5	40	0.3								
A537 steel	0.05	2	8	0.2	30	0.5	40	0.3								
409 st. steel	0.02	0.1	0.8	0.55	5	0.3	25	0.1							80	0.05
26 Cr-1 Mo steel	0.02	nil	0.04	0.6	10	0.05	10	0.15	40	0.05	40	0.05			80	0.15
304L st. steel	0.02	nil	0.04	0.2	30	0.15	40	0.3	60	0.15	60	0.15	100	0.05		
321 st. steel	0.02	nil	0.04	0.2	30	0.15	40	0.3	30	0.15	30	0.15	100	0.05		
316L st. steel	0.02	nil	0.04	0.3	10	0.1	15	0.25	60	0.15	60	0.15	100	0.05		
317L st. steel	0.02	nil	0.04	0.4	5	0.05	8	0.20	60	0.15	60	0.15	100	0.05		
Nitronic 33	0.02	nil	0.04	0.2	30	0.15	40	0.3	60	0.15	40	0.15	100	0.05		
JS 700	0.02	nil	0.04	0.2	3	0.15	6	0.3	40	0.15	40	0.15	30	0.05		
Ferralium 255	0.02	nil	0.04	0.3	10	0.1	15	0.25	50	0.15	50	0.10	100	0.05	80	0.05
Incoloy 825	0.02	nil	0.04	0.6	2	0.1	4	0.15	30	0.05	30	0.05	100	0.05		
Inconel 625	0.02	nil	0.04	0.7	1	0.1	2	0.1	30	0.05	30	0.05				
Ti Code 2	0.02	nil	0.04	0.8	1	0.05	2	0.05							200	0.1
Ti Code 12	0.02	nil	0.04	0.8	0.2	0.05	0.5	0.05							200	0.1
Zr 702	0.02	nil	0.04	0.8	0.2	0.05	0.5	0.05							200	0.1
Cu-Ni 30	0.02	0.06	0.2	0.3	0.6	0.3	1.6	0.3	20 ^c	0.1 ^c						

^a Data not to be used for prediction of corrosion rates.^b To convert mils/yr to $\mu\text{m/yr}$, multiply by 25.4.^c Dealloying phenomenon.

Table 7. Estimated costs of candidate metals.

Material	Raw material cost (plate) (\$/in. ³) ^a	Manufacturing cost for 1/2-in. wall- welded pipe (\$/in. ³) ^a	Total cost (\$/in. ³)
AISI 1020 steel	0.1	0.2	0.3
A537 steel	0.1	0.2	0.3
409 Ti stabil. st. steel	0.3	0.3	0.6
26 Cr-1 Mo steel	1.1	0.3	1.4
304L st. steel	0.4	0.2	0.6
321 st. steel	0.5	0.2	0.7
316L st. steel	0.5	0.2	0.7
317L st. steel	0.6	0.2	0.8
Nitronic 33 st. steel	0.4	0.2	0.6
JS 700 st. steel	1.0	0.3	1.3
Ferrallium 255 st. steel	0.7	0.5	1.2
Incoloy 825	1.2	0.5	1.7
Inconel 625	2.6	0.5	3.1
Ti Code 2	1.6	0.5	2.1
Ti Code 12	1.8	0.5	2.3
Zr 702	3.5	0.6	4.1
CDA 715 (copper-nickel 70/30)	1.0	0.4	1.4

^a To convert \$/in.³ to \$/cm³, multiply by 6.1×10^{-2} .

Table 9. Weldability parameters for candidate metals.^a

Material designation or composition	Preheat	Special interpass temp.	Post- heat treat	Special atm.	Low weld, HAZ ^b toughness	Non- standard process	Non- standard NDE	Non- econ. rel. to AISI 304	Special fit-up
AISI 1020 steel	0	0	0	0	0	0	0	0	0
A537 steel	0	1	0	0	0	0	0	0	0
409 Ti stabil. st. steel	1	1	1	0	1	0	0	1	0
26 Cr-1 Mo st. steel	0	0	1	1	1	0	0	1	1
304L st. steel	0	0	0	0	0	0	0	0	0
321 st. steel	0	0	0	0	0	0	0	0	0
316L st. steel	0	0	0	0	0	0	0	0	0
317L st. steel	0	0	0	0	0	0	0	1	0
Nitronic 33 st. steel	0	0	0	0	0	0	0	1	0
JS 700 st. steel	1	1	1	0	0	0	0	1	1
Ferrallium 255 st. steel	0	1	0	0	0	0	0	0	1
Incoloy 825	0	0	0	0	0	0	0	1	1
Inconel 625	0	0	0	0	0	0	0	1	1
Ti Code 2	0	0	0	1	0	0	0	1	1
Ti Code 12	0	0	0	1	1	0	1	1	1
Zr 702	0	0	0	1	1	0	0	1	1
CDA 715 (copper-nickel 70/30)	0	1	0	0	0	0	0	1	1

^a Yes (1) or no (0) special problems.

^b Heat-affected zone.

Table 8. Mechanical properties of candidate metals.

Material	Tensile strength (ksi) ^a	Yield strength at 800°C (ksi) ^a	Elongation (%) minimum static	Nil ductility temperature (°C) for 1/2-in.-thick plate	Fracture toughness minimum at -18°C	
					(ft-lb) ^b	(ksi-in. ^{1/2}) ^c
AISI 1020 steel	60	8	30	-18	8	—
A537 steel	80	8	22	-30	40	107
409 Ti stabil. st. steel	70	5	25	-29	20	—
26 Cr-1 Mo steel	70	7	20	-18	20	—
304L st. steel	80	12	40	< -148	100	142
321 st. steel	85	13	40	< -148	90	129
316L st. steel	80	13	40	< -148	110	150
317L st. steel	80	18	40	< -148	100	156
Nitronic 33	115	20	40	< -148	43	123
JS 700	85	19	40	< -148	100	147
Ferralium 255	124	25	25	-18	100	—
Incoloy 825	95	23	30	< -148	78	150
Inconel 625	135	45	40	< -148	44	130
Ti Code 2	50	1	21	< -148	30	65
Ti Code 12	70	3	18	-18	11	35
Zr 702	55	1	16	-18	11	35
CDA 715 (copper-nickel 70/30)	44	17	37	< -148	113	—

^a To convert ksi to MPa, multiply by 6.9.^b To convert ft-lb to joules, multiply by 1.36.^c To convert ksi-in.^{1/2} to MPA-m^{1/2}, multiply by 0.18.

— ATTACHMENT E —



Department of Energy
Nevada Operations Office
P. O. Box 14100
Las Vegas, NV 89114-4100

cc: Lynn
McCrigh

File

MAY 15 1984

Ralph Stein, Acting Deputy Associate Director, Geologic Repository Deployment,
DOE/HQ (RW-21) GTN

DOE POSITION RELATIVE TO THE USE OF COPPER AS THE WASTE PACKAGE MATERIAL

In response to your request, the following represents our proposed position regarding the use of copper as a waste package containment barrier material.

Consistent with the current direction on exploring the use of copper as a waste package material and the pending H.R. Bill 5369, we are aggressively addressing this issue. We are currently developing an R&D program which could be as large as \$1M in FY 1985 and \$2M in FY 1986 in anticipation of the passage of the bill and the appropriate funding being made available.

A meeting to identify the issues and to obtain input from representatives of the copper industry was held at Lawrence Livermore National Laboratory (LLNL) May 10, 1984. The meeting was attended by the following:

- L. B. Ballou - Lawrence Livermore National Laboratory (LLNL)
- R. D. McCright - Lawrence Livermore National Laboratory (LLNL)
- D. T. Peters - International Copper Research Association (ICRA)
- K. J. Kundig - Consultant to Copper Development Association (CDA)
- M. D. Valentine - U. S. Department of Energy (DOE)


The potential issues are identified in the enclosed draft "Consolidation of Copper as a High-Level Nuclear Waste Containment Material" by R. D. McCright (LLNL), and were discussed at the meeting. Comments and suggestions were requested from the representatives of the two associations. They have agreed to provide their comments by the end of May.

We expect that they will be involved in the evaluation activities that we plan to undertake. They have indicated that they are prepared to assist in the activities and are amenable to accepting DOE funding.

Based upon feedback from ICRA and CDA, LLNL will further define a material evaluation program to thoroughly investigate the ability of copper to effectively serve as a waste package material in a tuff environment.

In summary, we (DOE/NV) intend to respond enthusiastically and with an open mind to consider copper as a potential waste package material; we will assure that Mr. Hodel's pledge to Mr. Udall will be carried out. If, after conducting our evaluation program, copper emerges as a technically acceptable material, its overall acceptability could then be considered from economic and other points of view as well. This point will also be important to the State of Nevada since it is also a producer of copper. Unfortunately, the local mines and smelters have recently been closed by the poor economics of the copper market in the United States .

Should you require additional information, please advise me.



Donald L. Vieth, Director
Waste Management Project Office

WMPO:VFW-824

Enclosure:

As stated

cc w/encl:

L. D. Ramspott, LLNL, Livermore, CA

NNWSI Project File

W. W. Dudley, USGS, Denver, CO

D. T. Oakley, LANL, Los Alamos, NM

T. O. Hunter, SNL, 6310, Albq., NM

A. R. Hakl, W, Mercury, NV

M. E. Spaeth, SAI, Las Vegas, NV

R. D. McCright

9 May 1984

DRAFT

Consideration of copper as a container material to hold high-level nuclear wastes in geological disposal raises the following three general issues: (1) compatibility of copper with processes proposed for fabricating and handling the waste form and metal containers, (2) compatibility of copper with the physical and chemical environment in the geological repository, and (3) compatibility of copper with other components in the nuclear waste package. These three general issues will be developed in the following paragraphs.

(1) Compatibility of copper with processes proposed for fabricating and handling the waste form and metal containers

Present conceptual waste package designs incorporate different processes for each waste form. For defense and commercial high-level wastes, molten glass is poured into a metal canister and the canister welded closed by an autogenous process. For spent fuel packages, the clad fuel rods are encanistered and the canister welded closed by an inert gas arc process. Just prior to closure, the spent fuel canister is filled with an inert gas. Present conceptual waste package designs consider 304L stainless steel as reference canister material with other austenitic alloys as alternatives.

Consideration of Cu or Cu-base alloys for fabricating nuclear waste containers suggests the following technical concerns in the nuclear waste package process operations:

(a) The yield strength of copper and cupronickels are, respectively, about one-third to one-half that of 304L stainless steel (all materials compared in the fully annealed state). The density of copper is about 15% greater than that of stainless steel. For handling considerations, the container material must have sufficient impact strength to survive a 10-meter drop test. Thus,

compared to stainless steel, a thicker section of copper or a copper-base alloy will be required. A corrosion wastage allowance may be needed to overcome the expected higher corrosion rates of Cu in oxidizing environments. The result of all these factors is a substantially heavier, thicker, and more costly container.

(b) Copper presents some concerns in welding. For arc-welding of thick sections, the high thermal conductivity of Cu requires a high heat input. This results in a large heat-affected zone around the weld with grain growth and tendency toward oxygen pick-up and hot shortness in the weld. Special attention must be paid to oxygen as an impurity in the shielding gas. The phosphorus-deoxidized grades (CDA 120) and the cupronickels (CDA 706 and 715) are generally more readily welded by inert gas arc processes. Autogenous weld processes may be used but the problem may be attaining a full penetration weld of a thick cross section (one to several cm). For the final closure weld the process must be performed and inspected remotely and these operations appear to be more problematic with a thicker section to weld.

(c) Copper is often joined by brazing. Brazing can join thick sections. While at first this may seem to present difficulties because of galvanic differences between the braze metal (often silver-base) and the base metal, the two metals may in fact be compatible. In a coupled situation, the braze metal would be expected to act as the cathode so that the area ratio of cathode to anode is small and any corrosion of the anodic member would be distributed over a large area. The possible interaction between base and braze metal would need to be investigated for brazing to be considered as a viable joining process.

(d) The present process developed for casting vitrified reprocessed waste uses a pour canister of 304L stainless steel. This material was selected on the basis of its excellent oxidation resistance in air at temperatures developed on the canister surface during pouring (400-600°C). The minimal amount of scale formed on the canister during pouring and cooling operations (24-30 hours) minimizes the amount of surface decontamination. With a less oxidation resistant metal like copper, the amount of scale and subsequent decontamination may present problems in transporting and handling a

contaminated canister surface. The amount of clean-up required may abusively work the surface. A further consideration is that with the present process the temperature of the molten glass strikes the canister at 700-800°C. This is a high temperature with regard to copper (MP 1083°C) so that some deformation of the inner canister surface may be expected. Clearly, consideration of copper as a pour canister will involve a review of the glass casting procedure. The higher mechanical properties and expected better oxidation resistance of the cupronickels may make these materials more attractive as pour canister materials. If not used as the pour canister, copper could be used as the overpack around a stainless steel pour canister. In this arrangement, consideration in the repository design should be given to an overall larger waste package. Another consideration - to be discussed in 3c - is the possible detrimental interaction between the outer Cu container and the inner stainless steel container.

(e) Retrievability of spent fuel waste packages is an option for the first 50 years of repository operation. Deformation by creep of a low-strength, low-modulus of elasticity material such as copper at storage temperatures of 200-250°C during the 50-yr period may result in subsequent handling problems if the retrievability option were exercised.

(f) Borehole liners are needed if the retrievable waste packages are horizontally emplaced. Carbon steel is the principal candidate for lining boreholes. Were a carbon steel liner used and it corroded, the corrosion products (Fe^{+++} principally) may so accelerate corrosion of a copper canister.

(g) Quite different container forming operations could be pursued for copper. An example is the Swedish KBS design for hot isostatic pressing of a copper shell onto a spent fuel rod assembly filled with copper powder to form a solid spent fuel package. The cost of forming, transporting, and emplacing such a large and heavy package would need to be reviewed relative to the present conceptual designs for spent fuel canister fabrication, package assembly, and package emplacement.

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(2) Compatibility of copper with the physical and chemical environment in the geological repository

This issue is centered around the integrity of the copper container to withstand the physical and chemical environment and insure essential containment of the nuclear waste for the first 300-1000 years. The issue considers the possible failure and degradation modes that a copper container may encounter during this period and an assessment of the probability that these failure/degradation modes operate. For a repository located in the unsaturated zone in tuff, the dominant environments are steam/air mixtures. The surface temperature of the container remains above 95°C (boiling point of water at the proposed repository elevation) for long periods of time (10s to 100s of years). Water intrusion into the waste package environment is possible after the temperature has cooled below the boiling point. Gamma radiation emanating from the waste form can produce radiolysis-induced changes in the environment.

The performance of copper needs to be investigated particularly as it applies to specific environmental conditions for a repository in tuff. Specific items needing investigation are enumerated below:

(a) During the long period when the environment is comprised of air/steam mixtures, the surface temperature on the container ranges from 95-250°C. The time-temperature profile depends on several waste package and repository design features. Oxidation of the copper container in irradiated steam/air mixtures is the degradation mode in this period. Depending on the radiation dose rate, the irradiated environment may produce oxides of nitrogen (such as NO_2 , N_2O_4 , N_2O_5) and anhydrous HNO_3 , all of which may enhance the oxidation rate of the copper container.

(b) When resaturation of the waste package environment is possible, the entering water is believed to be oxidizing in nature (6 ppm dissolved O_2 , 10 ppm NO_3^-). Radiolysis of the water may make the environment more oxidizing by production of such species as nitrate ion, nitric acid, nitrite ion, nitrous acid, hydrogen peroxide, and oxygen. These strongly oxidizing species are known to produce general corrosion rates on the order of 10 $\mu\text{m/yr}$

to several cm/yr, depending on the temperature and concentration of these species in aqueous solution.

(c) Ammonia can be produced at least initially in the radiolysis of aerated aqueous solutions. Ammonia is corrosive to copper even in small concentrations and can cause stress corrosion cracking of many Cu-base alloys.

(d) Cu and Cu-base alloys undergo localized corrosion (pitting, crevice attack) in certain aqueous environments including domestic water supplies. A particular corrosion phenomenon associated with several copper alloys is selective leaching of the less-noble constituent.

(e) Cu-base alloys such as the 90-10 cupronickel (CDA 706) and 70-30 cupronickel (CDA 715) may offer greater general corrosion resistance in oxidizing environments than the relatively pure coppers such as electrolytic tough pitch (CDA 100-116), oxygen-free high-conductivity grades (CDA 101-107), and phosphorus deoxidized grades (CDA 120-122). On the other hand, the non-alloyed coppers are effectively immune to stress corrosion cracking and to selective leaching mechanisms.

(3) Compatibility of copper with other components in the nuclear waste package

This issue is centered around possible detrimental effects of a copper container on the performance of other components in the waste package, particularly the performance of the waste form in meeting the 10,000 year isolation objectives on release of radionuclides. Breach of the copper container by corrosion or by some other failure mode can allow transport of the repository environment to the inner components of the waste package. If water is present in the repository environment, corrosion products from the copper may be transported to the inner components of the waste package. Therefore, the following items should be considered:

(a) Interaction between copper and the aqueous environment with regard to the solubility of copper corrosion products in this environment.

DRAFT

(b) For spent fuel packages, reaction of copper corrosion products with Zircaloy cladding on spent fuel elements may accelerate failure of the cladding. There is evidence that Cu^{++} may cause stress corrosion cracking of the Zircaloy with a consequent increase in the release rate of fission products from the spent fuel. The specific reaction of copper ions and UO_2 is not known and needs to be investigated. The ability of copper and uranium to form highly soluble complex ions must be addressed.

(c) For vitrified reprocessed waste form packages, the reaction of copper corrosion products with the glass and subsequent leaching of radionuclides is not known and needs to be investigated. In the case where a copper overpack surrounds a stainless steel pour canister, an early failure of the outer container may accelerate an early failure of the inner container as Cu^{++} is known to provoke pitting attack on austenitic stainless steels.

DRAFT

— ATTACHMENT F —



copper development

association inc

Mailing Address:

Greenwich Office Park 2, Box 1840, Greenwich, CT 06836-1840 TELEX: 843784 CDAQRC (203) 625-8210

June 15, 1984

Mr. R.D. McCright
Lawrence Livermore National Laboratory
Mail Station L396
University of California
P.O. Box 808
Livermore, California 94550

Dear Mr. McCright:

Copper for Nuclear Waste Canisters

Continuing the discussion and correspondence begun when Dale Peters and Konrad Kundig visited you on May 10, this letter summarizes our current best judgement as to which copper metals merit inclusion in your investigation of copper for nuclear waste disposal canisters in the tuff environment.

Copper and its alloys are ideal candidates for the canister application. Copper is essentially a noble metal in the galvanic series; that and the fact that its alloys form passive, protective films are the basis of successful applications in a wide range of corrosive environments. The copper metals provide mechanical properties ranging from the moderate strength and maximum ductility of copper itself to strength equivalent to heat treated steels in precipitation hardened compositions. Copper and its alloys are routinely fabricated by the full range of commercial processes. The U.S. is essentially self-sufficient in copper and the main alloying elements are available in North America.

Five Candidates

After review with our industry task group, we believe there are five standard alloys which have the potential to perform well as the canister material in the tuff environment:

1. Copper No. C10200, Oxygen-Free Copper.
2. Copper Alloy No. C17200, Beryllium Copper.
3. Copper Alloy No. C18100, MZC Copper.
4. Copper Alloy No. C61300, Aluminum Bronze.
5. Copper Alloy No. C71500, Copper-Nickel, 30%

CDA Standards Handbook data sheets on each of the candidates

are enclosed. (We will send you additional data on alloys 2 and 3 above in a few days. These were not covered in the data forwarded by Melanie Pascale's letter of May 18.)

All of the alloys are in large-scale commercial use and for each there are examples of satisfactory performance under demanding conditions.

Copper C10200 is widely used in electrical and electronic applications as products ranging from thin strip and fine wire to extremely heavy sections and plates for particle accelerators. Oxygen-free copper, chosen for the Swedish disposal canisters and approved by the U.S. National Academy of Sciences, is included to provide a link to that program and a base line for comparing all the alloys.

Alloy C17200 is a precipitation-hardenable alloy that can achieve very high yield, creep and fatigue strengths and offers excellent corrosion resistance. It has been used successfully as repeater housings for transatlantic undersea cables. Of the five candidates, C17200 is the only one having a higher yield strength than Type 304 stainless steel.

Alloy C18100 is an oxygen-free material with small additions of magnesium, zirconium and chromium to achieve high strength through cold work and aging. It has the same virtues as oxygen-free C10200 and retains yield strengths above 50,000 psi at elevated temperatures. Although a recent development, MZC is being used on a large scale in fusion reactor prototype development work.

Alloy C61300 is an aluminum bronze that offers excellent resistance to high temperature oxidation. It is widely used commercially in mildly oxidizing environments at elevated temperatures, such as potash crystallizers and molds for glass container production.

Alloy C71500, 70-30 copper-nickel, is chosen for its excellent corrosion resistance in aggressive environments. For example, the alloy gives good service in seawater desalination plants and in power plant condenser air removal sections where it is exposed to steam environments contaminated with ammonia and other corrosive non-condensable gases. It is used at still higher temperatures in power plant feedwater heaters.

Fabricability

All five of the alloys can be readily worked and can be


joined using conventional commercial processes (see enclosed data sheets) as well as by diffusion bonding and electron beam welding. We foresee no difficulties whatsoever in fabricating a canister from any of these copper metals apart from the engineering development required (whatever the metal involved) to accomplish this in the nuclear waste canister context.

Suggested Research & Development

In view of the extensive knowledge and experience available on the five candidate materials, we think you should by-pass other considerations and concentrate your initial efforts on the single question of corrosion resistance under the anticipated service conditions. The combination of high temperature, oxidizing species, and radiation creates a harsh environment. We believe the most conclusive experiment is one that tests the metals in a simulated tuff repository environment, including radiation.

We in the copper industry would be glad to work with you in more detail in planning and setting up your experimental program and in locating needed materials and facilities. Please contact us if we can provide additional information.

Sincerely,



W. Stuart Lyman
Senior Vice President
Technical & Market Services

WSL/llp
Enc.

cc: Mr. Donald E. Vieth
Mr. Dale T. Peters

COPPER No. 102 (OXYGEN FREE)

Composition — percent

	Nominal	Minimum	Maximum
Copper (incl. Silver)	99.95	....
Residual Deoxidants	None	

Nearest Applicable A S T M Specifications

Flat Products	B48, B133, B152, B187, B272, B370, B432
Pipe	B42, B188
Rod	B12, B49, B124, B133, B187
Shapes	B124, B133, B187
Tube	B68, B75, B88, B111, B188, B280, B359, B372, B395, B447
Wire	B1, B2, B3, B33, B47, B116, B189, B246, B286, B298, B355

Physical Properties

	English Units	C. G. S. Units
Melting Point (Liquidus)	1981 F	1083 C
Melting Point (Solidus)	1981 F	1083 C
Density	.323 lb/cu in @ 68 F	8.94 gm/cu cm @ 20 C.
Specific Gravity	8.94	8.94
Coefficient of Thermal Expansion	.0000094 per °F from 68 F to 212 F	.0000170 per °C from 20 C to 100 C
Coefficient of Thermal Expansion	.0000096 per °F from 68 F to 392 F	.0000173 per °C from 20 C to 200 C
Coefficient of Thermal Expansion	.0000098 per °F from 68 F to 572 F	.0000177 per °C from 20 C to 300 C
Thermal Conductivity	226 Btu/sq ft/ft/hr/°F @ 68 F	.934 cal/sq cm/cm/sec/°C @ 20 C
Electrical Resistivity (Annealed)	10.3 Ohms (circ mil/ft) @ 68 F	1.71 Microhm-cm @ 20 C
Electrical Conductivity* (Annealed)	101 % IACS @ 68 F	.586 Megmho-cm @ 20 C
Thermal Capacity (Specific Heat)	.092 Btu/lb °F @ 68 F	.092 cal/gm/°C @ 20 C
Modulus of Elasticity (Tension)	17,000,000 psi	12,000 Kg/sq mm
Modulus of Rigidity	6,400,000 psi	4,500 Kg/sq mm

* Volume Basis

Typical Uses

ELECTRICAL: bus bars and bus conductors, and other electrical conductors, wave guides, copper to glass seals in electronic appliances

Common Fabrication Processes

Blanking, coining, coppersmithing, drawing, etching, forming and bending, heading and upsetting, hot forging and pressing, piercing and punching, roll threading and knurling, shearing, spinning, squeezing and swaging, stamping

Fabrication Properties

Capacity for Being Cold Worked Excellent
Capacity for Being Hot Formed Excellent
Hot Forgeability Rating (Forging Brass = 100) 65
Hot Working Temperature 1400-1600 F or 750-875 C
Annealing Temperature 700-1200 F or 375-650 C
Machinability Rating (Free Cutting Brass = 100) 20

Suitability for being joined by:

Soldering Excellent
Brazing Excellent
Oxyacetylene Welding Fair
Gas Shielded Arc Welding Good
Coated Metal Arc Welding Not Recommended
Resistance Welding { Spot Not Recommended
Seam Not Recommended
Butt Good

F-4

The values listed above represent reasonable approximations suitable for general engineering use. Due to commercial variations in composition and to manufacturing limitations, they should not be used for specification purposes. See applicable A.S.T.M. specification references.

(Continued on other side)

COPPER No. 102 (Continued)

Forms and Tempers
Most Commonly Used

Forms and Tempers Most Commonly Used		Annealed Tempers						Rolled or Drawn Tempers												Hot Finished Tempers			
		Nominal Grain Size mm																					
		.100	.070	.050	.035	.025	.015	Soft Anneal	Light Anneal	Eighth Hard	Quarter Hard	Half Hard	Three Quarter Hard	Hard	Extra Hard	Spring	Extra Spring	Drawn - General Purpose (1)	Hard Drawn (2)	Light Drawn - Bending (3)	As Hot Rolled	As Extruded	Special Tempers
FLAT PRODUCTS	Strip, Rolled																						
	Strip, Drawn																						
	Flat Wire, Rolled																						
	Flat Wire, Drawn																						
	Bar, Rolled																						
	Bar, Drawn																						
	Sheet																						
	Plate																						
	ROD																						
	WIRE																						
TUBE																							
PIPE																							
SHAPES																							

1. DRAWN - GENERAL PURPOSE temper is used for general purpose tube only, usually where there is no real requirement for high strength or hardness on the one hand or for bending qualities on the other.

2. HARD DRAWN temper is used only where there is need for a tube as hard or as strong as is commercially feasible for the size in question.

3. LIGHT DRAWN - BENDING temper is used only where a tube of some stiffness, but yet capable of readily being bent (or otherwise moderately cold worked) is needed.

Mechanical Properties

Form	Size Section in.	Temper	Tensile Strength ksi	Yield Strength		Elongation in 2 in. %	Rockwell Hardness			Shear Strength ksi	Fatigue Strength	
				(.5% Ext. under Load) ksi	(.2% Offset) ksi		F	B	30T		ksi	Million Cycles
FLAT PRODUCTS	.040 in.	.050 mm	32.0	10.0		45	40	-	-	22.0		
		.025 mm	34.0	11.0		45	45	-	-	23.0	11.0	100
		Eighth Hard	36.0	28.0		30	60	10	25	25.0		
		Quarter Hard	38.0	30.0		25	70	25	36	25.0		
		Half Hard	42.0	36.0		14	84	40	50	26.0	13.0	100
		Hard	50.0	45.0		6	90	50	57	28.0	13.0	100
		Spring	55.0	50.0		4	94	60	63	29.0	14.0	100
		Extra Spring	57.0	53.0		4	95	62	64	29.0		
		As Hot Rolled	34.0	10.0		45	45	-	-	23.0		
		.250 in.	32.0	10.0		50	40	-	-	22.0		
	.250 in.	.050 mm	32.0	10.0		50	40	-	-	22.0		
		Eighth Hard	36.0	28.0		40	60	10	-	25.0		
		Quarter Hard	38.0	30.0		35	70	25	-	25.0		
		Hard	50.0	45.0		12	90	50	-	28.0		
	1.0 in.	As Hot Rolled	32.0	10.0		50	40	-	-	22.0		
		Hard	45.0	40.0		20	85	45	-	26.0		
ROD	1.0 in.	.050 mm	32.0	10.0		55	40	-	-	22.0		
	.250 in.	Hard (40%)	55.0	50.0		10	94	60	-	29.0		
	1.0 in.	Hard (35%)	48.0	44.0		16	87	47	-	27.0	17.0	100
	2.0 in.	Hard (16%)	45.0	40.0		20	85	45	-	26.0		
	1.0 in.	As Hot Rolled	32.0	10.0		55	40	-	-	22.0		
WIRE	.080 in.	.050 mm	35.0			35*	-	-	-	24.0		
		Hard	55.0			1.5**	-	-	-	29.0		
		Spring	66.0			1.5**	-	-	-	33.0		
TUBE	1.0 in. OD X .065 in.	.050 mm	32.0	10.0		45	40	-	-	22.0		
		.025 mm	34.0	11.0		45	45	-	-	23.0		
		Light Drawn (15%)	40.0	32.0		25	77	35	45	26.0		
		Hard Drawn (40%)	55.0	50.0		8	95	60	63	29.0		
SHAPES	.500 in.	.050 mm	32.0	10.0		50	40	-	-	22.0		
		Hard (15%)	40.0	32.0		30	-	35	-	26.0		
		As Hot Rolled	32.0	10.0		50	40	-	-	22.0		
		As Extruded	32.0	10.0		50	40	-	-	22.0		

* Elongation in 10 inches.

** Elongation in 60 inches.

The values listed above represent reasonable approximations suitable for general engineering use. Due to commercial variations in composition and to manufacturing limitations, they should not be used for specification purposes. See applicable A.S.T.M. specification references.

COPPER ALLOY Nos. 172 and 173 (BERYLLIUM COPPER)

Composition — percent

	Copper Alloy No. 172			Copper Alloy No. 173		
	Nominal	Minimum	Maximum	Nominal	Minimum	Maximum
Copper	98.1	....	....	97.7	....	....
Beryllium	1.9	1.80	2.00	1.9	1.80	2.00
Lead	....	....	....	.40	.20	.6
Nickel + Cobalt	....	.20	....	....	.20	....
Ni + Fe + Co	....	....	.6	....	....	.6
Copper (incl. Ag) + Elements with Specific Limits	....	99.5	....	....	99.5	....

Nearest Applicable A S T M Specifications

	Copper Alloy No. 172	Copper Alloy No. 173
Flat Products	B194, B196	B196
Pipe		
Rod	B196	B196
Shapes		
Tube		
Wire	B197	

Physical Properties

	English Units	C. G. S. Units
Melting Point (Liquidus)	1800 F	980 C
Melting Point (Solidus)	1590 F	865 C
Density	.298 lb/cu in @ 68 F	8.26 gm/cu cm @ 20 C.
Specific Gravity	8.26	8.26
Coefficient of Thermal Expansion	per °F from 68 F to 212 F	per °C from 20 C to 100 C
Coefficient of Thermal Expansion	per °F from 68 F to 392 F	per °C from 20 C to 200 C
Coefficient of Thermal Expansion	.0000099 per °F from 68 F to 572 F	.0000178 per °C from 20 C to 300 C
Thermal Conductivity	62-75 Btu/sq ft/ft/hr/°F @ 68 F	.26-.31 cal/sq cm/cm/sec/°C @ 20 C
Electrical Resistivity (Annealed)	46.2 Ohms (circ mil/ft) @ 68 F	7.68 Microhm-cm @ 20 C
Electrical Conductivity* (Annealed)	22 % IACS @ 68 F	.128 Megmho-cm @ 20 C
Thermal Capacity (Specific Heat)	.10 Btu/lb °F @ 68 F	.10 cal/gm/°C @ 20 C
Modulus of Elasticity (Tension)	18,500,000 psi	13,000 Kg/sq mm
Modulus of Rigidity	7,300,000 psi	5,000 Kg/sq mm

*In the precipitation hardened condition

**Volume Basis

Typical Uses

HARDWARE: Bellows, bourdon tubing, diaphragms, fuse clips, fasteners, lock washers, springs, switch parts, relay parts, electrical and electronic components, retaining rings, roll pins

INDUSTRIAL: Valves, pump parts, spline shafts, rolling mill parts, welding equipment

Common Fabrication Processes

Blanking, drawing, forming and bending, turning, drilling, tapping

Fabrication Properties

Capacity for Being Cold Worked..... Excellent

Capacity for Being Hot Formed..... Good

Hot Forgeability Rating (Forging Brass = 100)

 Copper Alloy No. 172..... 40

 Copper Alloy No. 173..... Not Recommended

Hot Working Temperature..... 1200-1500 F or 650-825 C

Annealing Temperature..... 1425-1475 F or 775-800 C

Machinability Rating (Free Cutting Brass = 100)

 Copper Alloy No. 172..... 20

 Copper Alloy No. 173..... 50

Suitability for being joined by:

Soldering..... Good

Brazing..... Good

Oxyacetylene Welding..... Not Recommended

Gas Shielded Arc Welding..... Good

Coated Metal Arc Welding..... Good

Resistance Welding { Spot..... Good

 Seam..... Fair

 Butt..... Fair

The values listed above represent reasonable approximations suitable for general engineering use. Due to commercial variations in composition and to manufacturing limitations, they should not be used for specification purposes. See applicable A.S.T.M. specification references.

(Continued on other side)

COPPER ALLOY Nos. 172 and 173 (Continued)

Forms and Tempers
Most Commonly Used

Forms and Tempers Most Commonly Used		Annealed Tempers						Rolled or Drawn Tempers											Hot Finished Tempers				
		Nominal Grain Size mm																					
		.100	.070	.050	.035	.025	.015	Soft Anneal (a)	Light Anneal	Eighth Hard	Quarter Hard	Half Hard	Three Quarter Hard	Hard	Extra Hard	Spring	Mill Hardened (B)	Drawn - General Purpose (1)	Hard Drawn (2)	Light Drawn - Bending (3)	As Hot Rolled	As Extruded	Special Tempers
FLAT PRODUCTS	Strip, Rolled							•		•	•	•	•				•						
	Strip, Drawn																						
	Flat Wire, Rolled																						
	Flat Wire, Drawn																						
	Bar, Rolled							•			•												
	Bar, Drawn							•			•												
	Sheet																						
	Plate							•															
	ROD							•						•									
	WIRE							•		•	•	•	•										
	TUBE							•										•					
	PIPE																						
	SHAPES							•															

1. DRAWN - GENERAL PURPOSE temper is used for general purpose tube only, usually where there is no real requirement for high strength or hardness on the one hand or for bending qualities on the other.
4. Solution Heat Treated.

2. HARD DRAWN temper is used only where there is need for a tube as hard or as strong as is commercially feasible for the size in question.

3. LIGHT DRAWN - BENDING temper is used only where a tube of some stiffness, but yet capable of readily being bent (or otherwise moderately cold worked) is needed.

5. Special Mill Processing and Precipitation Treatment.

Mechanical Properties

Form	Size Section	Temper		Tensile Strength		Yield Strength .2% Offset		Elongation in 2"		Rockwell Hardness			Fatigue Strength	
		I	II	I	II	I	II	I	II	B	30T	C	ksi	Million Cycles
FLAT PRODUCTS	Under .186 in.	A	AT	70.0	175.0	32.0	155.0	45	6	60	58	38	36.0	100
		½H	½HT	80.0	185.0	70.0	165.0	25	4	80	70	40	40.0	100
		¾H	¾HT	92.0	195.0	82.0	175.0	15	3	92	77	41	44.0	100
		H	HT	110.0	200.0	104.0	180.0	5	2	99	81	42	44.5	100
		AM	-	105.0	....	82.0	....	20	-	-	-	20	....	....
		½HM	-	115.0	....	92.0	....	17	-	-	-	23	....	....
		¾HM	-	128.0	....	105.0	....	15	-	-	-	27	....	....
		HM	-	142.0	....	122.0	....	12	-	-	-	32	....	....
		XHM	-	168.0	....	148.0	....	7	-	-	-	37	....	....
		XHMS	-	182.0	....	160.0	....	6	-	-	-	39	....	....
ROD	All	A	AT	68.0	178.0	25.0	160.0	48	6	62	-	38	....	....
	Up to 3/8 in. incl.	H	HT	112.0	200.0	90.0	182.0	15	3	95	-	41	....	....
	Over 3/8 to 1 in. incl.	H	HT	105.0	195.0	90.0	178.0	15	5	95	-	41	....	....
	Over 1 in.	H	HT	100.0	190.0	90.0	175.0	15	3	95	-	41	....	....
WIRE		A	AT	68.0	178.0	28.0	160.0	35	3	-	-	-	....	....
		½H	½HT	102.0	190.0	82.0	175.0	10	2	-	-	-	....	....
		¾H	¾HT	122.0	200.0	100.0	185.0	5	1	-	-	-	....	....
		¾H	¾HT	142.0	210.0	120.0	190.0	2	1	-	-	-	....	....
		H	HT	152.0	212.0	125.0	195.0	1	1	-	-	-	....	....

Note: A - Solution Heat Treated
H - Hard (except for tempers using M designations)

T - Precipitation Heat Treated
AM through XHMS - Special Mill Processing and Precipitation Treatment

(I) As Supplied by Producer Mill

(II) Properties after Precipitation Hardening by Customer at 600F

The values listed above represent reasonable approximations suitable for general engineering use. Due to commercial variations in composition and to manufacturing limitations, they should not be used for specification purposes. See applicable A.S.T.M. specification references.

COPPER ALLOY No. 181 (MAGNESIUM - ZIRCONIUM - CHROMIUM COPPER)

PRELIMINARY

Composition — percent

	Nominal	Minimum	Maximum
Copper (incl. Silver)		98.45	
Magnesium	0.04	0.03	0.06
Zirconium	0.15	0.05	0.30
Chromium	0.80	0.40	1.20

Nearest Applicable A S T M Specifications

Wire B 624

Physical Properties

	English Units	C. G. S. Units
Melting Point (Liquidus)	1967 F	1075 C
Melting Point (Solidus)	— F	— C
Density	.319 lb/cu in @ 68 F	8.88 gm/cu cm @ 20 C.
Specific Gravity	8.88	8.88
Coefficient of Thermal Expansion	0.0000093 per °F from 68 F to 212 F	.0000167 per °C from 20 C to 100 C
Coefficient of Thermal Expansion	.0000102 per °F from 68 F to 392 F	.0000184 per °C from 20 C to 200 C
Coefficient of Thermal Expansion	.0000107 per °F from 68 F to 572 F	.0000193 per °C from 20 C to 300 C
Thermal Conductivity	187 Btu/sq ft/ft/hr/°F @ 68 F	0.773 cal/sq cm/cm/sec/°C @ 20 C
Electrical Resistivity (Annealed)	13 Ohms (circ mil/ft) @ 68 F	2.167 Microhm-cm @ 20 C
Electrical Conductivity* (Annealed)	80 % IACS @ 68 F	0.461 Megmho-cm @ 20 C
Thermal Capacity (Specific Heat)	0.094 Btu/lb °F @ 68 F	0.094 cal/gm/°C @ 20 C
Modulus of Elasticity (Tension)	18,200,000 psi	.2650 Kg/sq mm
Modulus of Rigidity	6,800,000 psi	4725 Kg/sq mm

Typical Uses

Electrical: Switches, circuit breakers, high temperature wire, contacts, semi-conductor bases, heat sinks, resistance welding tips and wheels.

Industrial: Continuous casting molds, fasteners, fusion energy targets, solar collectors.

Common Fabrication Processes

Hot-rolling, hot-forging, drawing, extruding, swaging, bending, heading, machining.

Fabrication Properties

Capacity for Being Cold Worked	Excellent	Suitability for being joined by:	
Capacity for Being Hot Formed	Excellent	Soldering.....	Excellent
Hot Forgeability Rating (Forging Brass = 100)		Brazing.....	Good
Hot Working Temperature 1450-1700 F or 790-925 C		Oxyacetylene Welding....	Not Recommended
Annealing Temperature 1110-1300 F or 600-700 C		Gas Shielded Arc Welding.....	Good
Machinability Rating (Free Cutting Brass = 100)		Coated Metal Arc Welding.....	
Recommended Solution Heat Treating and Aging Cycles		Resistance Welding { Spot...Not Recommended	
		Seam...Not Recommended	
		Butt.....	Fair
Solution Heat Treated and Aged	Solution Treating 1650-1790 F	Aging 750-930 F	Time 1 hr.
Solution Heat Treated, Cold Worked and Aged	1650-1790 F	750-930 F	1 hr.

The values listed above represent reasonable approximations suitable for general engineering use. Due to commercial variations in composition and to manufacturing limitations, they should not be used for specification purposes. See applicable A.S.T.M. specification references.

(Continued on other side)

COPPER ALLOY No. 181 (Continued)

Forms and Tempers
Most Commonly Used

Forms and Tempers Most Commonly Used		Annealed Tempers		Rolled or Drawn Tempers								Hot Finished Tempers					
		Nominal Grain Size mm						Solution Heat Treated	Solution Heat Treated and Cold Worked	Solution Heat Treated, Cold Worked and Aged	Solution Heat Treated, Cold Worked, Aged and Cold Worked	Solution Heat Treated and Aged	MIN Annealed	MIN Annealed and Cold Worked	As Hot Rolled	As Extruded	Special Tempers
		.100	.070	.050	.035	.025	.015										
FLAT PRODUCTS	Strip, Rolled																
	Strip, Drawn																
	Flat Wire, Rolled																
	Flat Wire, Drawn																
	Bar, Rolled																
	Bar, Drawn																
	Sheet																
	Plate																
	ROD																
	WIRE																
TUBE																	
PIPE																	
SHAPES																	

1. DRAWN - GENERAL PURPOSE temper is used for general purpose tube only, usually where there is no real requirement for high strength or hardness on the one hand or for bending qualities on the other.

2. HARD DRAWN temper is used only where there is need for a tube as hard or as strong as is commercially feasible for the size in question.

3. LIGHT DRAWN - BENDING temper is used only where a tube of some stiffness, but yet capable of readily being bent (or otherwise moderately cold worked) is needed.

Mechanical Properties

Form	Size Section in.	Temper	Tensile Strength ksi	Yield Strength		Elongation in 2 in. %	Rockwell Hardness			Shear Strength ksi	Fatigue Strength	
				(.5% Ext. under Load) ksi	(.2% Offset) ksi		F	B	30T		ksi	Million Cycles
Flat Products	0.04	CW 40%	67		62	6	-	-	-	-	-	-
	0.04	CW 40%, aged	72		66	10	-	-	-	-	-	-
Wire	0.160	CW 60%	70		63	6	-	-	-	-	-	-
	0.160	CW 60%, aged	75		68	11	-	80	-	-	-	-
	0.08	CW 75%	72		66	5	-	-	-	-	-	-
	0.08	CW 75%, aged	80		69	12	-	-	-	-	-	-
	0.08	CW 90%	73		66	4	-	-	-	-	-	-
	0.08	CW 90%, aged	85		75	13	-	-	-	-	-	-

COPPER ALLOY No. 613

Composition — percent

	Nominal	Minimum	Maximum
Copper	92.7	.....	.....
Iron	.....	.....	3.5
Tin	.3	.20	.50
Aluminum	7.0	6.0	8.0
Manganese	.....	.....	.50
Nickel	.....	.....	.50
Copper + Elements with Specific Limits	.....	99.5	.....

Nearest Applicable A S T M Specifications

Flat Products	B169, B171
Pipe	
Rod	B150
Shapes	
Tube	
Wire	

Physical Properties

	English Units	C. G. S. Units
Melting Point (Liquidus)	1915 F	1045 C
Melting Point (Solidus)	1905 F	1040 C
Density	.287 lb/cu in @ 68 F	7.95 gm/cu cm @ 20 C
Specific Gravity	7.95	7.95
Coefficient of Thermal Expansion	per °F from 68 F to 212 F	per °C from 20 C to 100 C
Coefficient of Thermal Expansion	per °F from 68 F to 392 F	per °C from 20 C to 200 C
Coefficient of Thermal Expansion	.0000090 per °F from 68 F to 572 F	.0000162 per °C from 20 C to 300 C
Thermal Conductivity	32 Btu/sq ft/ft/hr/°F @ 68 F	.13 cal/sq cm/cm/sec/°C @ 20 C
Electrical Resistivity (Annealed)	86.8 Ohms (circ mil/ft) @ 68 F	14.4 Microhm-cm @ 20 C
Electrical Conductivity* (Annealed)	12 % IACS @ 68 F	.070 Megmho-cm @ 20 C
Thermal Capacity (Specific Heat)	.09 Btu/lb °F @ 68 F	.09 cal/gm/°C @ 20 C
Modulus of Elasticity (Tension)	17,000,000 psi	12,000 Kg/sq mm
Modulus of Rigidity	6,400,000 psi	4,500 Kg/sq mm

*Volume Basis

Typical Uses

HARDWARE:	Nuts, bolts
INDUSTRIAL:	Corrosion resistant vessels, tanks, components, machine parts, piping systems, heat exchanger tube
MARINE:	Protective sheathing and fasteners
MUNITIONS:	Blending chambers, mixing troughs

Common Fabrication Processes

Blanking, drawing, forming and bending, cold heading, roll threading, welding

Fabrication Properties

Capacity for Being Cold Worked	.....Good
Capacity for Being Hot Formed	.....Good
Hot Forgeability Rating (Forging Brass = 100)	.....50
Hot Working Temperature	1450-1700 F or 800-925 C
Annealing Temperature	1125-1600 F or 600-875 C
Machinability Rating (Free Cutting Brass = 100)	.....30

Suitability for being joined by:

SolderingNot Recommended						
BrazingFair						
Oxyacetylene WeldingNot Recommended						
Gas Shielded Arc WeldingExcellent						
Coated Metal Arc WeldingGood						
Resistance Welding	<table> <tr> <td>Spot</td><td>.....Good</td></tr> <tr> <td>Seam</td><td>.....Good</td></tr> <tr> <td>Butt</td><td>.....Good</td></tr> </table>	SpotGood	SeamGood	ButtGood
SpotGood						
SeamGood						
ButtGood						

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The values listed above represent reasonable approximations suitable for general engineering use. Due to commercial variations in composition and to manufacturing limitations, they should not be used for specification purposes. See applicable A. S. T. M. specification references.

(Continued on other side)

COPPER ALLOY No. 613 (Continued)

Forms and Tempers
Most Commonly Used

Forms and Tempers Most Commonly Used		Annealed Tempers								Rolled or Drawn Tempers										Hot Finished Tempers				
		Nominal Grain Size mm																						
		.100	.070	.050	.035	.025	.015	Soft Anneal	Light Anneal	Eighth Hard	Quarter Hard	Half Hard	Three Quarter Hard	Hard	Extra Hard	Spring	Extra Spring	Drawn - General Purpose (1)	Hard Drawn (2)	Light Drawn - Bending (3)	As Hot Rolled	As Extruded	Special Tempers	
FLAT PRODUCTS	Strip, Rolled	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Strip, Drawn	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Flat Wire, Rolled	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Flat Wire, Drawn	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Bar, Rolled	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Bar, Drawn	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Sheet	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Plate	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	ROD	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	WIRE
	TUBE
	PIPE
	SHAPES

1. DRAWN - GENERAL PURPOSE temper is used for general purpose tube only, usually where there is no real requirement for high strength or hardness on the one hand or for bending qualities on the other.

2. HARD DRAWN temper is used only where there is need for a tube as hard or as strong as is commercially feasible for the size in question.

3. LIGHT DRAWN - BENDING temper is used only where a tube of some stiffness, but yet capable of readily being bent (or otherwise moderately cold worked) is needed.

Mechanical Properties

Form	Size Section in.	Temper	Tensile Strength ksi	Yield Strength		Elonga- tion in 2 in. %	Rockwell Hardness		Shear Strength ksi	Fatigue Strength	
				(.5% Ext. under Load) ksi	(.2% Offset) ksi		F	B 30T		ksi	Million Cycles
FLAT PRODUCTS	.125 in.	Soft Anneal.....	80.0	40.0	.....	40	- 82 -		52.0	28.0	100
	.500 in.	Soft Anneal.....	78.0	35.0	.....	42	- 81 -		50.0	26.0	100
	1.0 in.	Soft Anneal.....	76.0	33.0	.....	42	- 79 -		45.0	25.0	100
	3.0 in.	Soft Anneal.....	70.0	30.0	.....	40	- 78 -		42.0	21.0	100
ROD	.500 in.	Hard (25%).....	85.0	58.0	35	- 91 -		48.0
	1.0 in.	Hard (25%).....	82.0	55.0	35	- 90 -		45.0
	2.0 in.	Hard (25%).....	80.0	48.0	35	- 88 -		40.0

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COPPER ALLOY No. 715 (COPPER NICKEL, 30%)

Composition — percent

	Nominal	Minimum	Maximum
Copper	69.5	....	....
Lead	....	....	.05
Iron	.5	.40	.7
Zinc	....	....	1.0
Nickel	30	29.0	33.0
Manganese	....	....	1.0
Copper + Elements with Specific Limits	....	99.5	....

Nearest Applicable A S T M Specifications

Flat Products	B122, B151, B171, B402, B432
Pipe	B466, B467
Rod	B151
Shapes	
Tube	B111, B359, B395, B466, B467, B543, B552
Wire	

Physical Properties

	English Units	C. G. S. Units
Melting Point (Liquidus)	2260 F	1240 C
Melting Point (Solidus)	2140 F	1170 C
Density	.323 lb /cu in @ 68 F	8.94 gm /cu cm @ 20 C.
Specific Gravity	8.94	8.94
Coefficient of Thermal Expansion	per °F from 68 F to 212 F	per °C from 20 C to 100 C
Coefficient of Thermal Expansion	per °F from 68 F to 392 F	per °C from 20 C to 200 C
Coefficient of Thermal Expansion	.0000090 per °F from 68 F to 572 F	.0000162 per °C from 20 C to 300 C
Thermal Conductivity	17 Btu /sq ft /ft /hr /°F @ 68 F	.07 cal /sq cm /cm /sec /°C @ 20 C
Electrical Resistivity (Annealed)	225 Ohms (circ mil /ft) @ 68 F	37.5 Microhm-cm @ 20 C
Electrical Conductivity* (Annealed)	4.6 % IACS @ 68 F	.0267 Megmho-cm @ 20 C
Thermal Capacity (Specific Heat)	.09 Btu /lb °F @ 68 F	.09 cal /gm /°C @ 20 C
Modulus of Elasticity (Tension)	22,000,000 psi	15,500 Kg /sq mm
Modulus of Rigidity	8,300,000 psi	5,800 Kg /sq mm

* Volume Basis

Typical Uses

INDUSTRIAL: condensers, condenser plates, distiller tubes, evaporator and heat exchanger tubes, ferrules, salt water piping

Common Fabrication Processes

Forming and bending, welding

Fabrication Properties

Capacity for Being Cold Worked Good
Capacity for Being Hot Formed Good
Hot Forgeability Rating (Forging Brass = 100)
Hot Working Temperature 1700-1900 F or 925-1050 C
Annealing Temperature 1200-1500 F or 650- 825 C
Machinability Rating (Free Cutting Brass = 100) 20

Suitability for being joined by:

Soldering	Excellent
Brazing	Excellent
Oxyacetylene Welding	Good
Gas Shielded Arc Welding	Excellent
Coated Metal Arc Welding	Excellent
Resistance Welding { Spot	Excellent
Seam	Excellent
Butt	Excellent

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The values listed above represent reasonable approximations suitable for general engineering use. Due to commercial variations in composition and to manufacturing limitations, they should not be used for specification purposes. See applicable A.S.T.M. specification references.

(Continued on other side)

COPPER ALLOY No. 715 (Continued)

Forms and Tempers
Most Commonly Used

Forms and Tempers Most Commonly Used		Annealed Tempers						Rolled or Drawn Tempers										Hot Finished Tempers					
		Nominal Grain Size mm																					
		.100	.070	.050	.035	.025	.015	Soft Anneal	Light Anneal	Eighth Hard	Quarter Hard	Half Hard	Three Quarter Hard	Hard	Extra Hard	Spring	Extra Spring	Drawn — General Purpose (1)	Hard Drawn (2)	Light Drawn — Bending (3)	As Hot Rolled	As Extruded	Special Tempers
FLAT PRODUCTS	Strip, Rolled																						
	Strip, Drawn																						
	Flat Wire, Rolled																						
	Flat Wire, Drawn																						
	Bar, Rolled																						
	Bar, Drawn																						
	Sheet																						
	Plate																						
	ROD																						
	WIRE																						
TUBE																							
PIPE																							
SHAPES																							

1. DRAWN - GENERAL PURPOSE temper is used for general purpose tube only, usually where there is no real requirement for high strength or hardness on the one hand or for bending qualities on the other.

2. HARD DRAWN temper is used only where there is need for a tube as hard or as strong as is commercially feasible for the size in question.

3. LIGHT DRAWN - BENDING temper is used only where a tube of some stiffness, but yet capable of readily being bent (or otherwise moderately cold worked) is needed.

Mechanical Properties

Form	Size Section in.	Temper	Tensile Strength ksi	Yield Strength		Elonga- tion in 2 in. %	Rockwell Hardness			Shear Strength ksi	Fatigue Strength	
				(.5% Ext. under Load) ksi	(.2% Offset) ksi		F	B	30T		ksi	Million Cycles
FLAT PRODUCTS	1.0 in.	As Hot Rolled	55.0	20.0	. . . . .	45	-	35	-	. . . . .	. . . . .	. . . . .
TUBE	1.0 in. OD X .065 in	.025 mm	60.0	25.0	. . . . .	45	80	45	-	. . . . .	. . . . .	. . . . .
	4.5 in. OD X .109 in	.035 mm	54.0	. . . . .	. . . . .	45	77	36	-	. . . . .	. . . . .	. . . . .
ROD	1.0 in.	Half Hard (20%)	75.0	70.0	. . . . .	15	-	80	-	. . . . .	. . . . .	. . . . .

— ATTACHMENT G —

Table 1. Waste package design requirements and desirable design features.

A. Waste package design requirements derived from NRC 10 CFR 60 and 10 CFR 71

Waste packages shall be designed to do the following:

1. Contain the waste for 300 to 1000 years.
2. Maintain a release rate less than 10^{-5} per year of the radionuclide inventory present at 1000 years.
3. Maintain retrievability for 50 years after emplacement of the first waste package.
4. Control criticality so as not to exceed an effective multiplication factor (k_{eff}) of 0.95 unless more than two unlikely changes occur.
5. Maintain temperatures below limits of the waste forms, which are 773 K (500°C) for WV/DHLW glass, 673 K (400°C) for CHLW glass, and 623 K (350°C) for spent fuel cladding.
6. Prevent release of radioactive material in excess of applicable federal and state standards after a drop test of two times the waste package length onto an unyielding surface, at the minimum anticipated temperature.
7. Prevent release of radioactive material in excess of applicable federal and state standards after sustaining a 1073 K (800°C), 30-minute fire test.
8. Prevent release of radioactive material in excess of applicable federal and state standards under expected loads during or after transportation, handling, emplacement, retrieval, and seismic events. Further, these loads must not compromise long-term performance.
9. Retain legible, externally labeled identification as long as retrievability is required.
10. Meet federal regulatory requirements for transportation of high level nuclear waste.
11. Meet requirements with consideration for cost-effectiveness, including direct package costs and related repository system costs through the operational period.

B. Desirable waste package design features

Waste package designs will do the following:

1. Use standardized components whenever possible.
2. Emphasize simplicity and ease of fabrication.
3. Be technically conservative.
4. Use conventional materials and fabrication techniques.
5. Be compatible with all waste processing, transportation and emplacement operations.

